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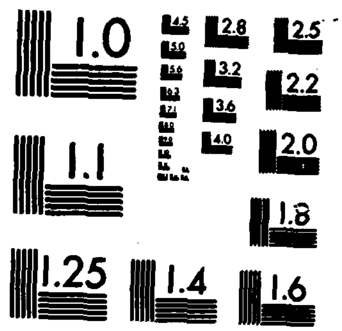

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Annual Scientific Report

on

ADVANCED DIAGNOSTICS FOR REACTING FLOWS

Contract F49620-83-K-0004

Prepared for

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For the Period

October 1, 1983 to September 30, 1984

Submitted by

R. K. Hanson, Principal Investigator
L. Hesselink, Co-Principal Investigator

HIGH TEMPERATURE GASDYNAMICS LABORATORY
Mechanical Engineering Department
Stanford University

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19. ABSTRACT

Progress is reported for the fourth year of an interdisciplinary program to innovate modern diagnostic techniques applicable to reacting and plasma flows. Research topics include: 1) fiber optic absorption/fluorescence sensors employing tunable ultraviolet, visible and infrared laser sources for species measurements; 2) wavelength-modulation spectroscopy, using rapid-scanning ultraviolet, visible and infrared laser sources, for absorption and fluorescence measurements of species, temperature and absorption lineshapes; 3) quantitative flow visualization, including temporally and spatially resolved species and temperature measurements in a plane, using laser-induced fluorescence; 4) quantitative particle visualization in spray flames using Mie scattering; 5) multiple-point velocity visualization; 6) advanced solid-state camera/computer systems for high-speed and high-resolution recording, processing and display of flow visualization data; 7) plasma diagnostics, utilizing planar laser-induced fluorescence and wavelength modulation techniques; 8) optical processing and phase conjugation studies; and 9) investigation of other new diagnostic concepts.

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TABLE OF CONTENTS

1.0 INTRODUCTION

Progress is reported for the fourth year of an interdisciplinary program to innovate modern diagnostic techniques applicable to reacting and plasma flows. Research topics include: (1) fiber optic absorption/fluorescence sensors employing tunable UV visible and IR laser sources for species measurements; (2) wavelength-modulation spectroscopy, using rapid-scanning IV, visible and IR laser sources, for absorption and fluorescence measurements of species, temperature and absorption line-shapes; (3) quantitative flow visualization, including temporally and spatially resolved species and temperature measurements in a plane, using laser-induced fluorescence; (4) quantitative particle visualization in spray flames using Mie scattering; (5) multiple-point velocity visualization; (6) advanced solid-state camera/computer systems for high-speed and high-resolution recording, processing and display of flow visualization data; (7) plasma diagnostics, utilizing planar laser-induced fluorescence and wavelength modulation techniques; (8) optical processing and phase conjugation studies; and (9) investigation of other new diagnostic concepts.

2.0 PROJECT SUMMARIES

Included in this section are summaries of progress in each of seven project areas. In most cases, each project summary contains the following subsections: (a) Introduction; (b) Scientific Merit; (c) Status Report; (d) Publications and Presentations; (e) Personnel. Additional descriptions of this work may be found in the cited publications and in our previous scientific reports (November 1981, November 1982, and November 1983).

2.1 Fiber Optic Absorption/Fluorescence Sensors

Introduction

Optical fibers provide a convenient and flexible means of linking expensive and environmentally sensitive laser sources with remote and possibly hostile test facilities. Additionally, fiber links facilitate multiplexed laser measurements, that is the use of one laser to make measurements at a number of locations. With regard to combustion and plasma needs, optical fibers offer perhaps the best prospect for extending some of the laser-based diagnostic techniques developed in small-scale laboratory experiments to larger-scale systems, particularly those with limited optical access.

With optical fiber technology, it becomes possible to consider measurements of a wide variety of physical quantities using various sensing schemes. In our work, we have been primarily interested in gaseous species and temperature measurements, and we have focused our efforts on the use of laser absorption and fluorescence which offer advantages with regard to sensitivity and simplicity of operation and interpretation. In the past few years we have reported on a series of approaches and devices (see publications listed at end of this section) for combustion measurements, using various laser sources (tunable IR diode lasers and both cw and pulsed tunable UV/visible dye lasers). As our past work in this area is well documented, we emphasize in this report our most recent activity involving the use of a fiber optic link to enable absorption-based measurements of NCO spectral parameters in a

shock tube located in a separate building 60 meters from the dye laser source.

Scientific Merit

This research seeks to enable the application of spectroscopy-based schemes for remote measurements of gaseous properties in reacting flows. Such schemes are critically needed for flows with poor optical access or where the test environment precludes local placement of a laser source. Our approach is unique in that it seeks to combine recently developed tunable laser sources with novel absorption or fluorescence probes. The resulting, relatively simple diagnostics are well suited to meet a variety of practical measurement requirements and hence have the potential for significant impact on various scientific and engineering aspects of combustion and propulsion. In addition, our work has contributed substantially to the fundamental spectroscopic data base for high temperature gases.

Status Report

We limit our discussion here to recent unpublished work. The reader is referred to the publications list at the end of this section for a full description of past work.

Our major activity during this reporting period has been to complete measurements of NCO spectral parameters using a fiber optic absorption technique to probe NCO generated in a shock tube. The species NCO has been proposed, on theoretical grounds, as a combustion intermediate of some importance in connection with the chemistry of nitrogen species in combustion. Until now, however, NCO has not been detected in a high temperature system. In our work we have: investigated the electronic absorption spectra of NCO ($B \leftarrow X$ and $A \leftarrow X$ bands), found an optimum wavelength for detection, modified our Ar^+-pumped cw ring dye laser to operate at this near-UV wavelength (440 nm, $A \leftarrow X$ band), installed a 60 meter optical fiber link between the laser and the shock tube lab, and performed incident shock wave tests to evaluate the spectral absorption parameters of NCO at high temperature.

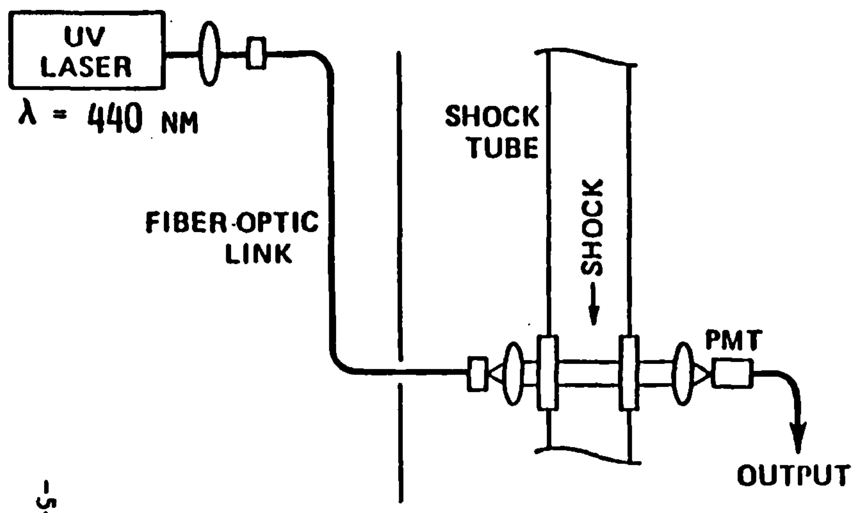
A schematic of the experiment and typical results are shown in Fig. 1. The laser source was a ring dye laser (Spectra-Physics 380A) operating on stilbene (S3) dye and pumped by the UV lines (1.9 W, all lines) of an Ar^+ laser (Spectra-Physics 171-18). The output of the laser was amplitude stabilized (Coherent 307 Noise Eater), yielding power levels of 5-10 mW at the input of the 60 meter fiber link (200 micron fused silica fiber, Superguide).

The quantity measured was the fractional absorption following shock-wave production of a fixed amount of NCO. Variations in the absorption as a function of laser wavelength, as shown in Fig. 1 (for T=1430K, P=0.6 atm), enable determination of the relevant Voigt parameter A and subsequently the collision-broadened linewidth for NCO broadened by Ar. The absolute absorption, together with the known level of NCO present, leads to a value for the electronic oscillator strength. (Details of this work have been submitted for publication; see publication 7 below.)

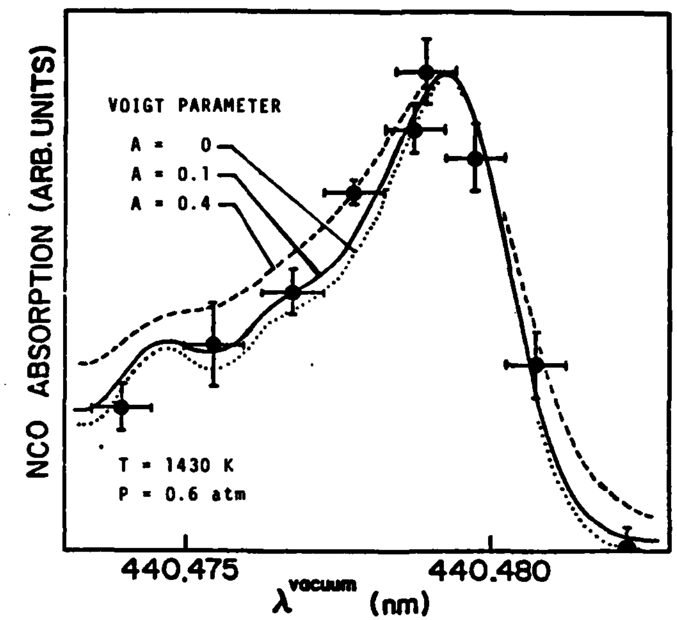
The significance of this work is threefold: (1) we have established a method for quantitatively monitoring NCO and have made the first measurements of NCO in a high temperature system; (2) we have determined oscillator strength and collision-broadening parameters for NCO; and (3) we have demonstrated the utility of fiber optic links for sensitive, quantitative species measurements at locations removed from the laser source. The latter accomplishment suggests the potential of using expensive and sensitive laser sources for measurements at several locations, thereby increasing the utility factor of such systems and enabling sharing of facilities between different experiments and research groups.

Three other projects related to fiber optic sensors have been initiated and can be mentioned briefly: (1) we have begun to investigate the use of coherent fiber bundles for transmission of quantitative visualization data from systems with limited optical access; (2) we have been working, thus far unsuccessfully, to acquire samples of recently developed infrared fibers (3-10 micron transmission) which we hope to use in research on remote laser-monitoring of infrared-active species, such as CO, CO_2, H_2O and various hydrocarbons; and (3) we have performed

SUCCESSFUL USE OF FIBER-OPTIC LINK TO REMOTELY MEASURE SPECTRAL PARAMETERS OF NCO



Fiber-Optic Link to
Shock Tube Experiment



HIGH TEMPERATURE ABSORPTION USED TO INFER NCO OSCILLATOR STRENGTH AND BROADENING FACTOR

- FIBER OPTIC LINK ENABLES USE OF LASER SOURCES FOR REMOTE MEASUREMENTS IN HOSTILE SYSTEMS
- MULTIPLE MEASUREMENT LOCATIONS WITH SINGLE LASER DEMONSTRATED
- FIRST OBSERVATION OF NCO AT HIGH TEMPERATURES
- TECHNIQUE ENABLES DETERMINATION OF SPECTRAL PARAMETERS AT HIGH TEMPERATURES

Fig. 1. Shock tube measurements of NCO spectral absorption coefficient using a remotely located dye laser.

some preliminary work on remote laser-absorption sensing of metal atoms and oxides, using visible diode or dye lasers, as a possible means of aircraft engine control or monitoring.

Publications and Presentations

Presentations

1. G. Kychakoff and R.K. Hanson, "Optical Fiber Probe Using Tunable Laser Absorption Spectroscopy for Combustion Measurements," presented at 1981 Los Alamos Conference on Optics, April 1981.

2. S.M. Schoenung and R.K. Hanson, "Laser Absorption Sampling Probe for Spatially and Temporally Resolved Combustion Measurements," presented at 1981 Conference on Lasers and Electro-Optics (CLEO), Washington, June 1981.

3. S.M. Schoenung and R.K. Hanson, "Temporally and Spatially Resolved Measurements of Fuel Mole Fraction in Turbulent CO Diffusion Flame," paper WSS/CI 81-33 at Western States Section, Combustion Institute meeting, Phoenix, October 1981.

4. G. Kychakoff and R.K. Hanson, "Tunable Laser Absorption/Fluorescence Fiberoptic Probe for Combustion Measurements," paper WSS/CI 81-50 at Western States Section, Combustion Institute meeting, Phoenix, October 1981.

5. G. Kychakoff, R.D. Howe and R.K. Hanson, "Spatially Resolved Combustion Measurements Using Crossed-Beam Saturated Absorption Spectroscopy," paper THM2 at CLEO '82, Phoenix, Az., April 14-16, 1982.

6. M.A. Kimball-Linne, G. Kychakoff, R.K. Hanson and R.A. Booman, "A Fiber Optic Fluorescence Probe for Species Measurements in Combustors," paper 82-50 at Western States Section, Combustion Institute meeting, Livermore, Ca., October 11-12, 1982.

Publications

1. S.M. Schoenung and R.K. Hanson, "CO and Temperature Measurements in a Flat Flame by Laser Absorption Spectroscopy and Probe Techniques," Combustion Science and Technology 24, 227-237 (1981).

2. S.M. Schoenung and R.K. Hanson, "Laser Absorption Sampling Probe for Spatially and Temporally Resolved Combustion Measurements," Applied Optics 21, 1767-1771 (1982).

3. S.M. Schoenung and R.K. Hanson, "Temporally and Spatially Resolved Measurements of Fuel Mole Fraction in a Turbulent CO Diffusion Flame," 19th Symposium (International) on Combustion, The Combustion Institute, pp. 449-458 (1982).

4. G. Kychakoff and R.K. Hanson, "Optical Fiber Probe Using Tunable Laser Absorption Spectroscopy for Combustion Measurements," The Los Alamos Conference on Optics, 81, D.L. Liebenbert, Ed., Proc. SPIE 288, 236 (1982).

5. R.K. Hanson, S. Salimian, G. Kychakoff and R.A. Booman, "Shock Tube Absorption Measurements of OH Using a Remotely Located Dye Laser," Applied Optics, 21, 641 (1983).

6. G. Kychakoff, M.A. Kimball-Linne and R.K. Hanson, "Fiber-Optic Absorption/Fluorescence Probes for Combustion Measurements," Applied Optics 22, 1426 (1983).

7. M.Y. Louge and R.K. Hanson, "Shock Tube Study of NCO Spectroscopy Using a Remotely Located Dye Laser," J. Quant. Spectrosc. and Radiat. Transfer, in press.

8. M.Y. Louge and R.K. Hanson, "High Temperature Kinetics of NCO," Comb. and Flame 58, 291 (1984).

Personnel

Ronald K. Hanson	Professor, Mechanical Engineering
Susan Schoenung	Graduate Student, Mechanical Engineering (Ph.D. awarded in June 1982)
Mark A. Kimball-Linne	Graduate Student, Mechanical Engineering (Ph.D. awarded in December 1984)
Michel Y. Louge	Graduate Student, Mechanical Engineering (Ph.D. awarded in December 1984)
George Kychakoff	Assistant Professor (Acting) Mechanical Engineering (Ph.D. expected in March 1985)
Richard A. Booman	Research Engineer, Mechanical Engineering

2.2 Wavelength Modulation Spectroscopy

Introduction

Recent improvements in tuning rates of narrow-linewidth laser sources offer opportunities for new diagnostic techniques based on wavelength modulation spectroscopy concepts. Wavelength modulation spectroscopy refers to laser absorption or laser-induced fluorescence measurements carried out with a rapid-tuning single mode laser. In

essence this method involves quickly scanning a tunable cw laser across one or more isolated absorption transitions and recording the spectrally resolved absorption line profile using either absorption or fluorescence detection. Our laboratory has played a lead role in establishing this measurement technique, using both infrared and UV/visible lasers, particularly for probing combustion gases and plasmas.

A primary advantage of wavelength modulation is that it provides a simple means of discriminating against continuum extinction and luminosity effects which can seriously hinder conventional laser absorption or fluorescence measurements in two-phase combustion flows and high-luminosity plasmas. Moreover, recording the fully resolved absorption line eliminates the need for uncertain linewidth assumptions in converting measured absorption (or fluorescence) to species concentration or temperature. Previously in our laboratory, in AFOSR-sponsored work, we demonstrated the utility of the wavelength modulation concept for combustion measurements involving infrared-active species using a commercially available rapid-tuning infrared diode laser.

Unfortunately, rapid-tuning dye lasers, needed for accessing a variety of important radical species which absorb in the near UV and visible, are not commercially available. Recognizing the importance of such a capability, we have in the past three years developed a novel (and simple) modification to a commercial ring dye laser which increases the scan repetition rate by three orders of magnitude (from about 4 Hz to 4 kHz) for short scans (up to 5 cm^{-1} = 150 GHz), and we have recently incorporated intracavity frequency doubling into the dye laser to permit access to UV wavelengths. Operation in the UV is critial for access to a variety of important combustion and plasma species.

Scientific Merit

This is the first dye laser system we are aware of which enables fast single-mode scans over spectral regions encompassing complete absorption lines (~ 30 GHz at combustion conditions). This capability provides several new opportunities for combustion and plasma research. In connection with combustors where particulates or droplets are

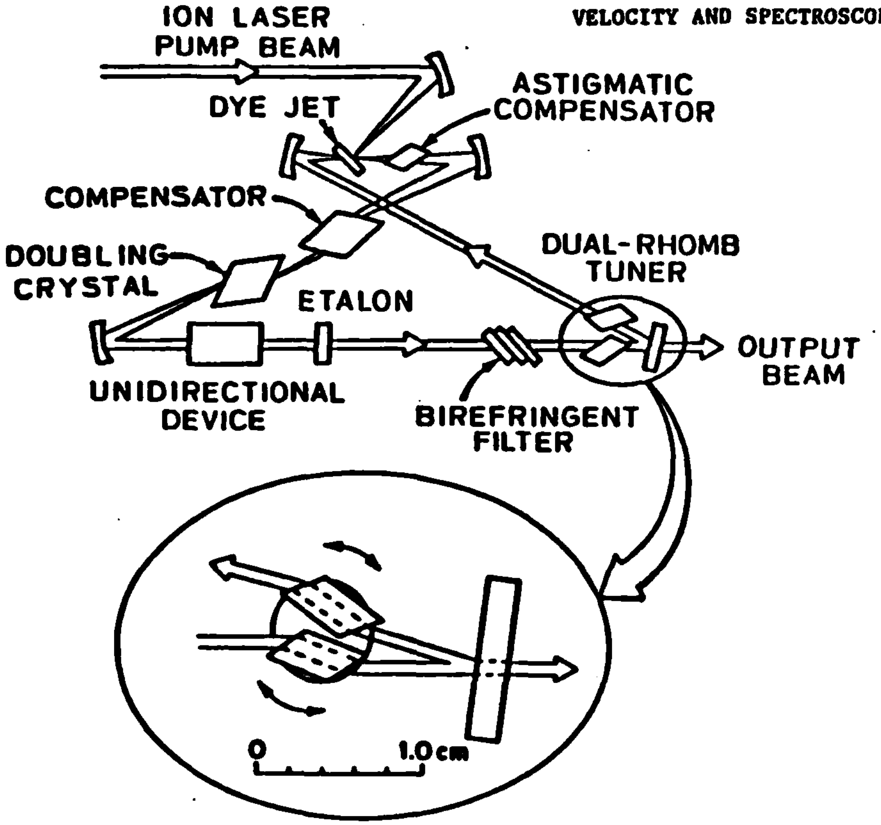
present, wavelength-modulation techniques can now be applied to discriminate between the gaseous absorption or fluorescence of interest and interfering continuum extinction. For plasma flows which may be highly luminous, wavelength modulation should provide a means of distinguishing the spectrally varying signal of interest from the intense continuum background. In unsteady flows or in devices where transient phenomena are of interest, fast measurements of fully-resolved absorption or fluorescence lines can be used for time-resolved determinations of species and temperature. Finally, the significance of fast-scanning capability for basic spectroscopic measurements should be noted. For example, we have recently demonstrated the feasibility of recording fully resolved absorption lines in shock tube flows. Such experiments provide first-time capability for obtaining a variety of fundamental data including important quantities such as collision linewidths, oscillator strengths and heats of formation; these parameters are needed to enable quantitative absorption and fluorescence measurements of species in combustion and plasma flows.

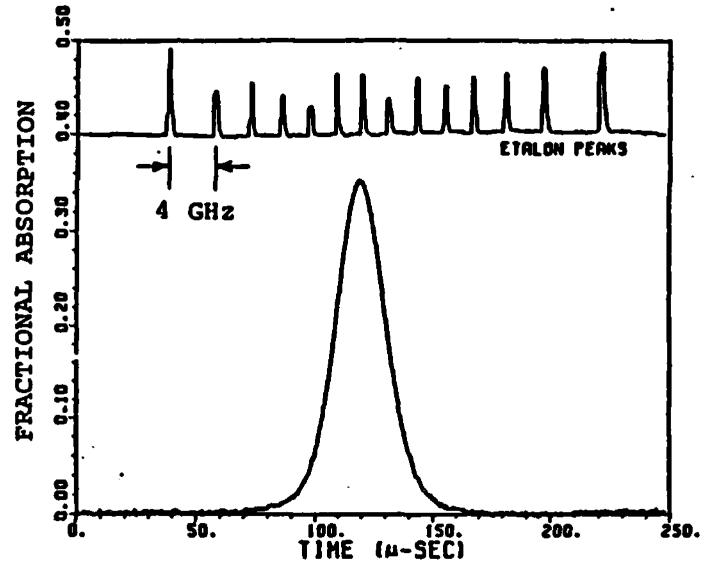
Status Report

A schematic diagram of the dye laser modification and an example of the system capability to monitor an isolated UV absorption line of OH in a flame are shown in Fig. 1. In brief, a rotating dual-element device, which changes the effective laser pathlength as it rotates, is installed in one corner of the ring laser adjacent to the output mirror. Use of two elements guarantees that the alignment of the beam (inside and outside of the cavity) does not change while the wavelength is changing. The tuning elements are mounted on the shaft of a commercial galvanometer which mounts conveniently in the standard ring cavity of our Spectra-Physics ring dye laser.

The tuner was demonstrated initially at visible wavelengths, providing continuous, single-mode scans of up to 5 cm^{-1} (150 GHz) at 4 kHz. Recently we have been able to extend this capability into the UV by installing a doubling crystal into the same cavity. Experiments with an AD*A doubling crystal, oven and mount (Spectra-Physics model 398A) show

RAPID SCANNING RING DYE LASER ENABLES NEW WAVELENGTH-MODULATION CONCEPTS FOR MEASURING SPECIES, TEMPERATURE, VELOCITY AND SPECTROSCOPIC PARAMETERS





SINGLE SWEEP RECORD OF FULLY RESOLVED OH ABSORPTION LINE OBTAINED BY PASSING TUNABLE LASER BEAM THROUGH FLAME.

- MODIFICATION IMPROVES SCANNING RATE OF LASER FROM 4 Hz → 4 kHz (60 GHz SCAN)
- SYSTEM PROVIDES FIRST HIGH-SPEED, HIGH SPECTRAL RESOLUTION CAPABILITY FOR STUDIES OF TRANSIENT PHENOMENA
- WAVELENGTH MODULATION CONCEPT ENABLES QUANTITATIVE ABSORPTION AND FLUORESCENCE MEASUREMENTS IN 2-PHASE FLOWS
- APPLICATIONS INCLUDE STUDIES IN FLAMES, SHOCK TUBES, SUPERSONIC FLOWS, COMBUSTION TUNNELS
- SYSTEM ENABLES UNIQUE MEASUREMENT OF BASIC PARAMETERS IN HIGH TEMPERATURE GASES (F-NUMBERS, LINESHAPES, ΔH_f)
- CONCEPT APPLICABLE FOR UV, VISIBLE AND NEAR IR WAVELENGTHS

Fig. 1 Schematic diagram of fast-scanning ring dye laser and typical data obtained in a flame.

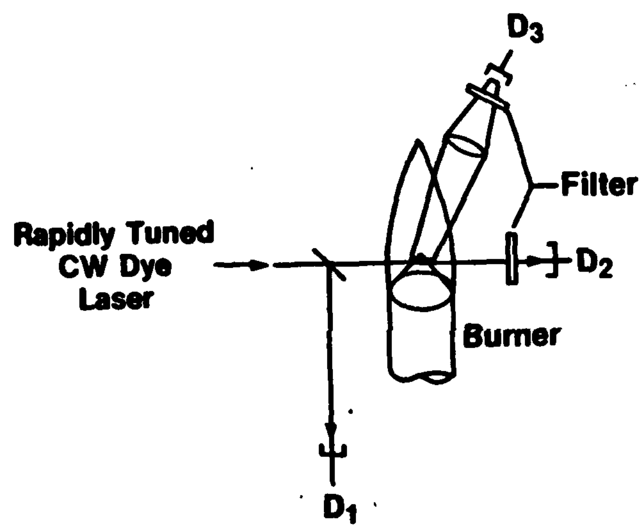
excellent performance (see Fig. 1), with output in excess of 10 mW at 309 nm (with a pump power of only 4 W all lines) and single mode scans of more than 100 GHz at 4 kHz repetition rate. We have been contacted by several researchers in other laboratories who are anxious to obtain this extended capability.

We have utilized this new tuner in two novel experiments, one conducted with a shock tube and one in a flame. In the shock tube experiment, the laser was used to record fully resolved absorption line profiles of OH over a range of post-shock conditions. In brief, the center frequency of the repetitively scanning laser was set on a known UV line of OH, and the beam was passed through the shock tube to enable recording of absorption line profiles behind incident shock waves. Mixtures of $H_2/O_2/Ar$ were shock heated to provide relatively constant levels of OH at known conditions. These experiments (see publication 6 for details) provide the first fully resolved, radical species absorption spectra recorded in a shock tube. Use of the fast-scanning laser in conjunction with shock tube methods provides several new opportunities for fundamental research on spectral and thermochemical properties of high temperature gases.

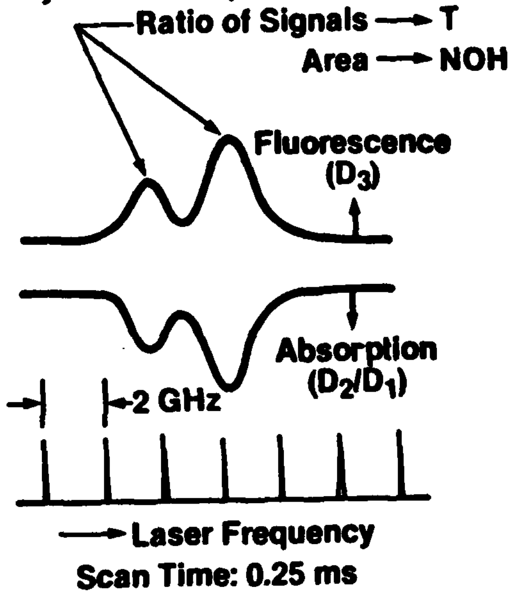
The second novel experiment which we have conducted involves combined absorption and fluorescence measurements in a flame. A simplified schematic diagram of the experiment indicating the essential features of the set-up and an illustration of the type of data recorded is shown in Fig. 2. In this work we have chosen to scan a portion of the OH absorption spectrum encompassing two transitions. This is an important aspect of our measurement strategy, because it enables inference of both temperature (from the relative strengths of the two lines) and species concentration (from absolute measurements of the area of one of the lines). The capability for simultaneous temperature and species concentration measurements demonstrated here using one laser source is quite exciting, particularly since the method appears capable of monitoring these quantities at high repetition rates. At present, CARS measurements, which can yield temperature but not minor species, are capable of only about 10 Hz repetition rate. The successful development

Rapid Wavelength-Modulation Spectroscopy

- Simultaneous Temperature and Species Measurements in a Flame and Plasma.



Fully Resolved Spectra of Two Transitions.



- Data Rate Increased From 4 to 4000 Hz by Two-Element Optical Scanner
- Ratio of Fluorescence Peaks Eliminates Need for Absolute Intensity Calibration in Sooting or Dense Flames
- Method Applicable to Two Phase Flows such as Sooting Flames and Spray Flames.
- Peak Ratio Strategy Enables Real-Time Temperature Monitoring

Hanson & Rea/ Stanford Univ.

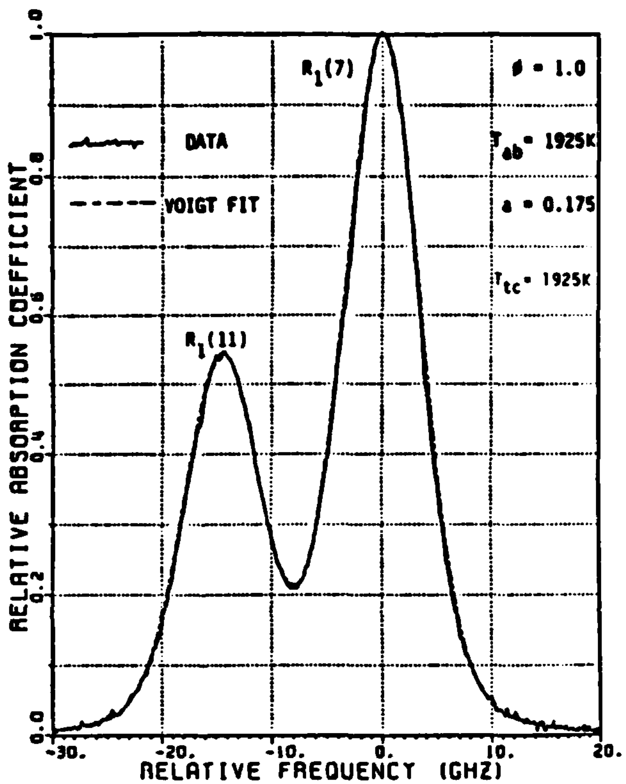
Fig. 2 Wavelength modulation spectroscopy: Approach and key features.

of a method yielding both temperature and species concentration at kilohertz repetition rates would therefore represent a major diagnostics advance. Although challenges remain, this is our goal and good progess is being made.

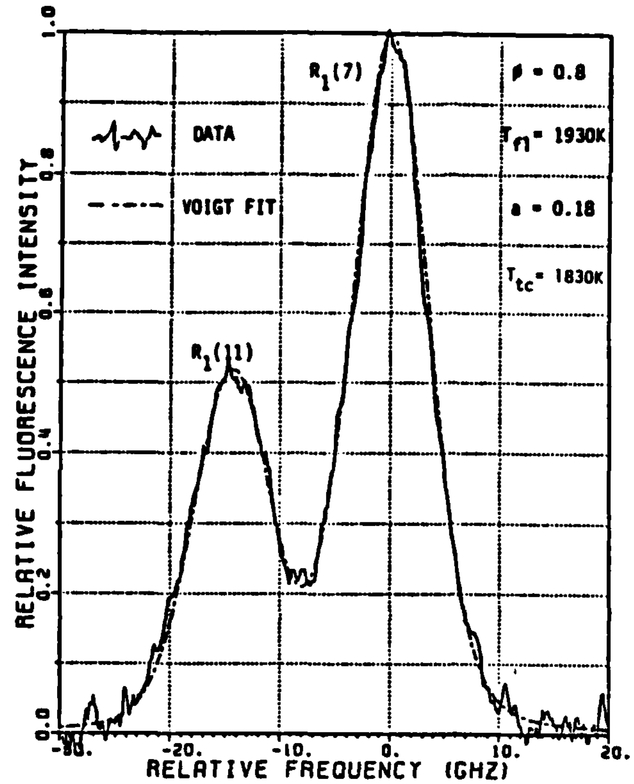
Examples of typical absorption and fluorescence data obtained in near-stoichiometric CH_4-air flat flames are shown in Fig. 3. For absorption (see left-hand panel of Fig. 3) the quantity plotted is the logarithm of the fractional transmission, normalized by the peak value, for a single-sweep (about 200 microsecond duration) scan of the laser. The data are fit using a best-fit Voigt profile analysis in which temperature is the principal unknown. The inferred temperature, 1925 K, is in excellent agreement with radiation-corrected thermocouple readings. The accuracy of the absorption-based temperature is extremely good; we estimate an uncertainty of under 1.5%. It must be remembered, of course, that this is a line-of-sight measurement, and while such measurements will be useful for many purposes they do not yield the spatial resolution needed for fundamental studies of turbulence. As of this writing, we have not yet extracted values of OH concentration from these records, although we anticipate no problems in doing so.

Similar, single-sweep fluorescence data (for a somewhat leaner flame) are shown in the right-hand panel of Fig. 3, again plotted together with a best-fit theoretical profile enabling determination of temperature. These data are noisier, owing to the much smaller signal with fluorescence, but the results are still very encouraging in that the fluorescence temperature agrees within a few percent with the thermocouple value.

Finally we note two very recent activities, both of which are at an early stage. The first effort involves broadening the operating range of the ring laser to include wavelengths outside the current range of 292-309 nm. The approach being considered is to use angle-tuned (rather than temperature-tuned) phase matching, with a lithium iodate doubling crystal. This work is still in the planning phase. The second topic is an exploratory study in which we hope to demonstrate laser-induced fluorescence, using wavelength modulation, in shock-heated gases. Such



Single sweep absorption trace and Voigt fit for wavelength modulation experiment in a flat flame burner; $\phi = 1.0$.



Single sweep fluorescence trace and Voigt fit for wavelength modulation experiment in a flat flame burner; $\phi = 0.8$.

- Good Agreement Between Spectroscopic (T_{ab}, T_{fl}) and Thermocouple (T_{tc}) Temperatures
- Simple (Peak Ratio) Analysis Could Enable Real-Time Temperature Monitoring

Fig. 3 Best-fit Voigt profiles and inferred temperatures for absorption and fluorescence records of OH in a CH_4/air flame. The inferred temperatures (T_{ab} and T_{fl}) are seen to agree well with the thermocouple values (T_{tc}).

measurements offer prospects for determining electronic quench rates in high temperature gases. Necessary shock tube modifications have now been completed and experiments should begin shortly.

Publications and Presentations

1. E.C. Rea, Jr., and R.K. Hanson, "Rapid Extended Range Tuning of Single-Mode Ring Dye Lasers," Applied Optics 22, 518 (1983).

2. E.C. Rea, Jr. and R.K. Hanson, "Fast-Scanning UV Ring Dye Laser for Combustion Research," presented at CLEO '83, Baltimore (May 1983).

3. R.K. Hanson, S. Salimian and E.C. Rea, Jr., "Laser Absorption Techniques for Spectroscopy and Chemical Kinetics Studies in a Shock Tube," ed. R. Archer and B. Milton, Sydney Symposium Publishers, 594-601 (1983).

4. R.K. Hanson, "Tunable Diode Laser Measurements in Combustion Gases," SPIE Vol. 438, pp. 75-83 (1983); also presented at 1983 meeting of Soc. Photographic and Inst. Engineers, San Diego, August 1983.

5. E.C. Rea, Jr. and R.K. Hanson, "Fully Resolved Absorption/Fluorescence Lineshape Measurements of OH Using a Rapid-Scanning Ring Dye Laser," paper 83-66 at the fall meeting of the Western States Section/Combustion Institute, Los Angeles, CA, October 1983.

6. E.C. Rea, Jr., S. Salimian and R.K. Hanson, "Rapid-Tuning Frequency-Doubled Ring Dye Laser for High Resolution Absorption Spectroscopy in Shock-Heated Gases," Applied Optics, 23, 1691-1694 (1983).

Personnel

Ronald K. Hanson	Professor, Mechanical Engineering
E.C. Rea, Jr.	Graduate Student, Mechanical Engineering (Ph.D. Expected in December 1985)

2.3 Quantitative Flow Visualization

Introduction

The utility of flow visualization as a diagnostic in studies of fluid mechanics and combustion is well established. Until recently, however, most visualization techniques have been qualitative and based on line-of-sight approaches poorly suited for flows with three-dimensional characteristics. With the recent development of laser-based light scattering techniques, it has become possible to obtain spatially and temporally resolved quantitative records of flow properties throughout a plane (and ultimately throughout a volume) using sheet illumination and a scattering technique such as Raman, fluorescence or Mie scattering. Work along these lines is now in progress at Stanford, Yale, SRI, Sandia (Livermore), and the Aeropropulsion Lab at Wright Field. As an example of the capability of these new methods, in our laboratory at Stanford we are now able to make instantaneous (8 nsec), multiple-point (10^4 flow-field points) measurements of species (OH, NO and Na) in a variety of laboratory flames using planar laser-induced fluorescence (PLIF). The sensitivity demonstrated thus far with molecular species is in the 10's of ppm range, with spatial resolution typically much better than 1 mm. Of equal importance, we have recently demonstrated variations of this approach which yield temperature (see below) and velocity (see Section 2.4) at multiple points without particle seeding. In addition we are beginning to combine PLIF visualization with Mie scattering techniques for studies in burning sprays (see below). These new techniques provide significant advances in measurement capability with potential scientific impact extending well beyond the field of combustion for which the methods were originally developed.

Scientific Merit

This is a fast-moving area of research with the potential to stimulate scientific advances in several fields, including but not limited to fluid mechanics, combustion and plasma sciences. Development of these visualization techniques may also contribute to related technologies, such as lasers and image processing, and provide fundamental data for

fields such as spectroscopy. Our goals are: (1) to establish means off acquiring and processing orders-of-magnitude more information (data) on flows than can be obtained with single-point measurements; (2) to establish techniques for visualizing quantities (such as pressure and vorticity) not previously available with optical methods; and (3) to establish methods for simultaneous measurements of multiple flowfield parameters and their fluctuating values. In order to develop advanced diagnostic systems with such potential, we must meet a number of interdisciplinary scientific challenges ranging from innovation of novel physical sensing processes to solution of problems involving the processing, display and even the interpretation of such expanded data sets. A new aspect of our work will be to establish data bases for selected flows, with the aim of stimulating the development of models which exploit the 2-d data provided by PLIF.

Status Report

Our work on quantitative visualization using planar laser-induced fluorescence has been detailed in a series of papers and reports (see list at end of this section), and so here we focus only on very recent activities not yet available in the literature. For convenience and clarity we provide separate status reports on: Species Visualization, Temperature Visualization, Spray Flame Visualization, and System Improvements.

(a) Species Visualization

Previously we have applied PLIF to visualize OH, Na, NO and I_2 in several flows. Recently we have worked to develop measurement capability for O_2 and C_2, as we discuss briefly below. Molecular oxygen is a critical species in many combustion studies, but is usually considered to be inaccessible by optical techniques as it absorbs strongly only in the UV below 200 nm. In addition, fluorescence is known to be weak owing to strong predissociation effects. Two factors may mitigate this conventional viewpoint: (1) the recent development of tunable VUV laser sources, particularly excimer and Raman-shifted excimer lasers; and (2) the fact that absorption transitions of interest in characterizing high

temperature gas systems may be relatively free of absorption interferences from layers of colder oxygen present in air.

Over the past year we have performed a literature survey to familiarize ourselves with relevant past work, and we have developed computer codes to allow prediction of O_2 absorption and fluorescence spectra as a function of temperature and of excitation wavelength. The calculations are complex and will not be described here, but in summary we find that absorption/fluorescence using either an ArF excimer laser at 193 nm or Raman-shifted ArF at 179 nm appears quite promising for detecting O_2 over a range of temperatures. Our confidence in this idea was further increased with a recent 1984 paper by Massey at UC San Diego who demonstrated single-point LIF measurements of O_2 number density and temperature, in a static cell near room temperature, using two tunable ArF lasers. We are now working actively toward laboratory experiments of our own to develop an O_2 visualization scheme, and at the same time we are investigating, by computer calculations with our O_2 spectroscopy program, candidate schemes for visualizing temperaure, pressure and O_2 mole fraction based on O_2 fluorescence.

Our interest in visualizing C_2 stems from its possible use in monitoring combustion flame fronts (often accompanied by radical overshoots) in gaseous diffusion flames and in burning fuel sprays. The status of the work is that single-point LIF measurements have recently been made in C_2H_2-air flames, and optimum wavelengths for excitation and detection have been established. Currently we are setting up to perform single-point measurements in a spray flame, and subsequently we plan to attempt PLIF measurements.

(b) Temperature Visualization

Temperature is a parameter of obvious importance in characterizing reacting flowfields, and hence a scheme for quantitative visualization of temperature would have broad application in combustion and plasma-related research. An ideal temperature visualization scheme would be sensitive, easy to calibrate, and would involve, for simplicity, only a single laser source. Although laser-induced fluorescence has been

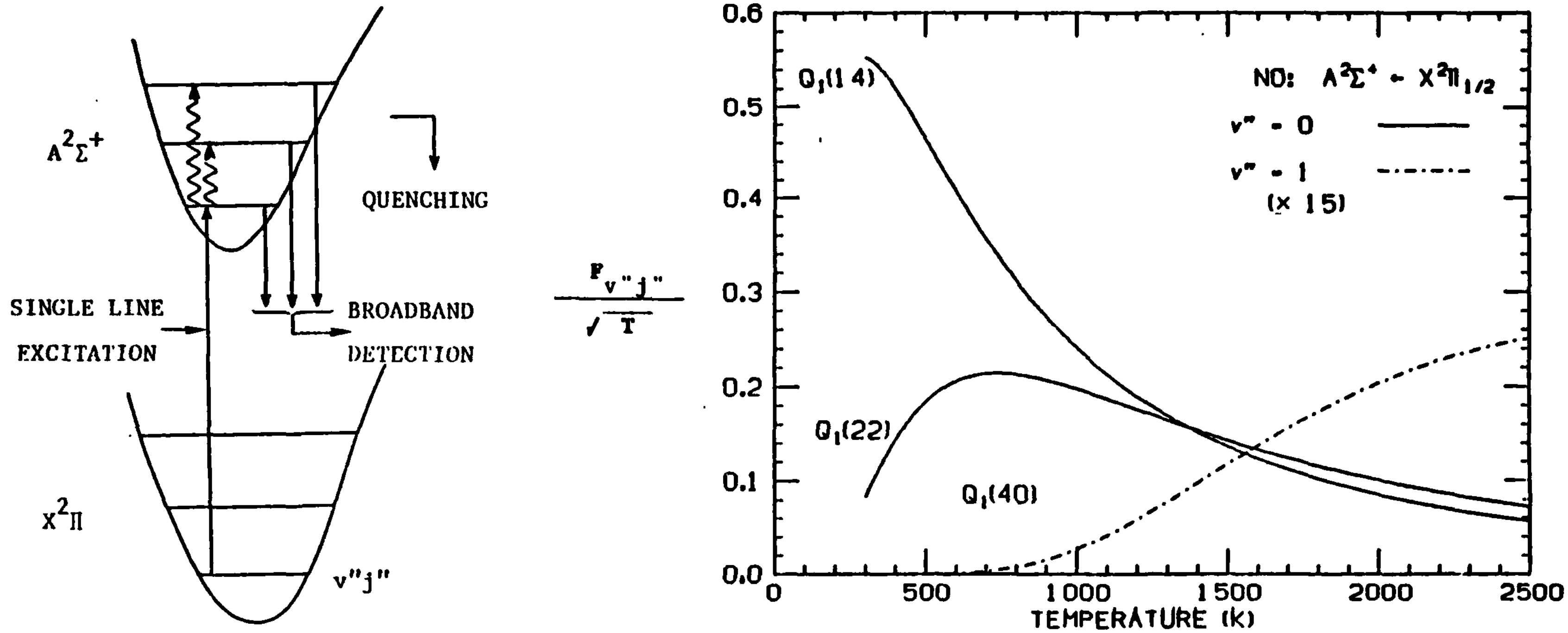
demonstrated for single-point temperature measurements, and very recently (by Svanberg et al., in Sweden, and Cattolica, at Sandia) for multiple-point measurements, these workers have employed two laser sources and, as a result, were only able to work in steady flames. Here we report a PLIF scheme which offers several advantages, including the use of only one laser source.

The strategy which we employ is to seed the flow uniformly with a non-reactive tracer species such as NO. Assuming linear (non-saturated) excitation using a spectrally broad (greater than the absorption line-width) pump laser, with broadband fluorescence detection and a uniform laser intensity distribution, the fluorescence intensity emanating from a point in the flowfield is given simply by

$$I_F = C\, n_i\, f_{vj}\, A/(A + Q) = C\, X_i\, f_{vj}/\sqrt{T} \qquad (1)$$

where C represents a group of known quantities, n_i is the number density of the absorber i, f_{vj} is the temperature-dependent Boltzmann fraction in the absorbing state (v,j), and A/A+Q is the photon yield (fraction of absorbed photons re-emitted into the detection bandwidth). For present purposes we assume that the Einstein coefficient for spontaneous emission, A, is much smaller than the electronic quench rate, Q, and that Q may be represented by $n\sigma\bar{c}$, where n is the total number density, σ is an effective cross-section and $\bar{c}$ is the mean molecular speed proportional to $T^{1/2}$; thus $A/A+Q \approx A/n\sigma\bar{c}$. Under conditions where σ may be regarded as a constant, and using the symbol X_i for the mole fraction of i (i.e., n_i/n), we obtain Eq. (1). Thus if the mole fraction of i is fixed the fluorescence intensity I_F is a known function of temperature alone.

This approach for temperature visualization (see Fig. 1) has the important advantage of requiring a single excitation wavelength (and hence a single laser). The sensitivity of the fluorescence signal to temperature depends on the quantity $f_{vj}/\sqrt{T}$, and hence the lower level quantum states v,j (vibration, rotation) may be chosen to optimize the signal in the temperature region of interest. Calibration may be



FLUORESCENCE EQUATION $\rightarrow$ $S \sim N_{NO} \times F_{v''j''} \times \dfrac{A}{A + Q}$

ASSUMPTIONS $\rightarrow$ $A << Q$, $Q = N\, \sigma\, \bar{v}$, $\bar{v} \sim \sqrt{T}$

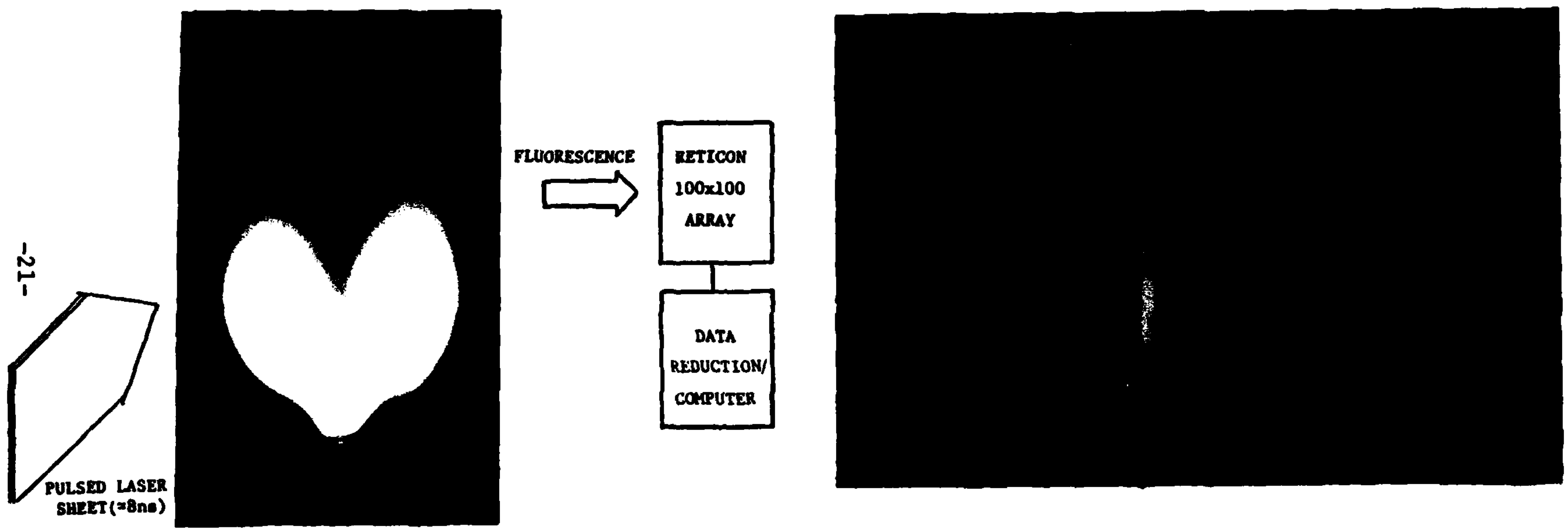
RESULT $\rightarrow$ $S \sim [N_{NO}/N] \times [F_{v''j''} / \sqrt{T}]$

Fig. 1 Excitation/detection scheme for temperature visualization and plot of fluorescence signal (S) sensitivity to temperature.

APPROACH

2-D TEMPERATURE MEASUREMENT

- LASER INDUCED FLUORESCENCE YIELDS INSTANTANEOUS 2-D TEMPERATURE FIELDS



ROD-STABILIZED CH_4/AIR FLAME

DIGITAL TEMPERATURE CONTOURS (10*mm* x 10*mm* REGION)

- FIRST TECHNIQUE FOR INSTANTANEOUS 2-D TEMPERATURE MEASUREMENTS
- NOVEL SINGLE-WAVELENGTH TECHNIQUE CAN BE SELF-CALIBRATING
- POTENTIAL APPLICATION TO UNSTEADY REACTING AND NONREACTING FLOWS

Fig. 2 Approach and results for temperature visualization technique.

Hanson & Seitzman/Stanford Univ.

achieved simply if the temperature is known at any flowfield point or region. Alternatively, if the function $f_{vj}/\sqrt{T}$ has a peak value within the temperature range present in the flowfield, then the calibration factor follows directly from the maximum signal observed. This method is limited, however, to flowfields where the double-valued nature of $f_{vj}/\sqrt{T}$ versus T introduces no ambiguity. In general, corrections are needed to account for nonuniform laser illumination, nonuniform pixel responsivity and background light levels.

A sample result showing the temperature contours obtained with a single laser shot (8 nsec) in a rod-stabilized flame is presented in Fig. 2. Here premixed CH_4 and air at atmospheric pressure flow vertically over a 1.5 mm diameter horizontal rod, resulting in a roughly V-shaped flame stabilized by the rod. The fuel lean (equivalence ratio ≃ 0.6) mixture is seeded with approximately 2000 ppm of NO, which may be regarded as non-reactive for these conditions. A vertical sheet (3 cm x 0.2 mm) of laser light near $\lambda = 225.6$ nm, produced by mixing the frequency-doubled output of a Nd:YAG-pumped dye laser with the residual 1.06 μm beam, is used to excite a single line in the $A^2\Sigma^+(v=0) \leftarrow X^2\Pi_{1/2}(v=0)$ NO band. The digital images of the fluorescence intensity, emanating from a 10 mm x 10 mm region, were processed to yield the temperature contours shown in Fig. 2. For this case, obtained using the $Q_1(22)$ line which has a peak in the function $f_{vj}/\sqrt{T}$ at 740K, the calibration was achieved by searching for the maximum signal (present on both sides of the rod) and setting the temperature at these locations at 740K. Again, use of different v,j states allows some flexibility in emphasizing different temperature regimes.

Current work with temperature visualization is directed toward refining the experimental set-up and procedures for this constant mole fraction approach, extending its application to other flows, and also to investigating the sensitivity of the NO quench rate to combustion gas composition at high temperatures. Alternative approaches utilizing cw laser excitation are also under study.

(c) Spray Flame Visualization

During the past year we have initiated new work to establish PLIF and planar Mie scattering (PMS) techniques in evaporating and burning fuel sprays. We regard this combined development of PLIF and PMS as a logical extension of our effort on quantitative visualization. Further, the development of such capability for measurements in two-phase flows is critical for studies in practical combustors and for fundamental research on droplet and solid propellant combustion.

Thus far we have: (1) completed assembly of a small-scale spray combustion facility; (2) set up an optical arrangement and made preliminary photographic and photodiode array measurements of Mie scattering with laser sheet illumination; (3) performed Mie scattering calculations to aid in the interpretation of PMS measurements; and (4) begun design of the optical arrangement for PLIF species and temperature visualization in the spray burner facility.

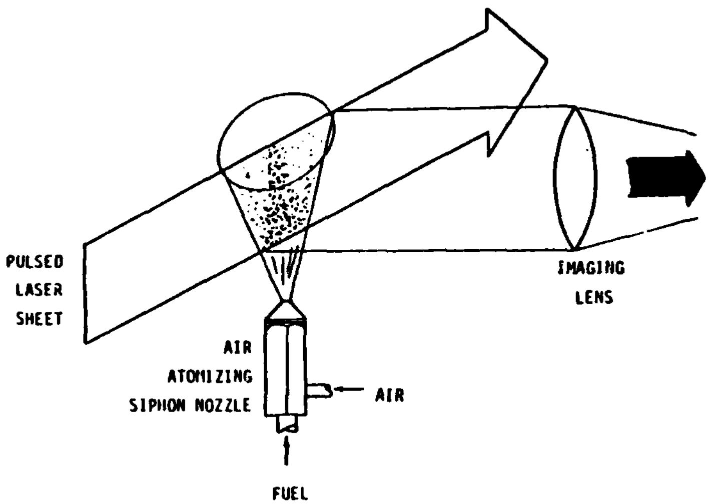
A schematic diagram and some representative PMS results for a burning spray are shown in Fig. 3. The fuel was n-heptane, flowing at a rate of about 0.2 gallons/hr from an air-atomizing siphon nozzle (Delevan), and the size of the region imaged was about 10 cm x 10 cm. Pulsed illumination, freezing the flow, was provided by a Nd:YAG-pumped dye laser operating near 590 nm. In the case of the photographic record, the image is acquired with a 1-2 second exposure which includes 10-20 individual laser pulses (each of which freezes the flow) and accumulated flame emission, while in the case of the unintensified photodiode array the image is for a single pulse and flame emission is excluded with a filter.

The significance of this initial work is to confirm the feasibility of PMS recording of sprays, using a photodiode array and in the presence of combustion, and to indicate the utility of this approach for determining droplet spacing and density. (It should be noted that the current approach does not provide droplet sizing information.) Our goal is to establish the capability for simultaneous PMS droplet distribution measurements and PLIF measurements of key species and temperature in

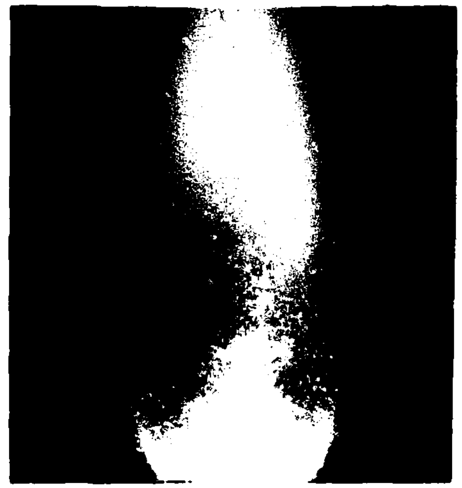
APPROACH

QUANTITATIVE FIELD VISUALIZATION IN BURNING SPRAYS

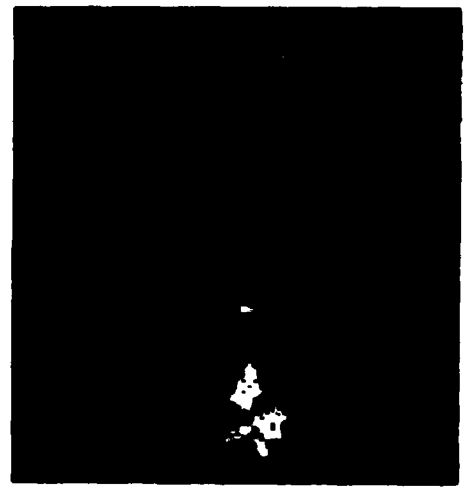
- PULSED LASER SHEET ILLUMINATION WITH RIGHT-ANGLE DETECTION YIELDS INSTANTANEOUS VISUALIZATION OF 2-D DROPLET FIELD



TECHNIQUE: ELASTIC SCATTERING



PHOTOGRAPHIC IMAGE



DIGITAL IMAGE

- TECHNIQUE WILL ENABLE STUDY OF DROPLET FIELD - FLOW FIELD INTERACTIONS
- POTENTIAL FOR FIRST SIMULTANEOUS MEASUREMENTS OF DROPLET, TEMPERATURE AND SPECIES FIELDS

Fig. 3 Approach and sample results for planar Mie scattering (PMS) in a burning spray.

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burning sprays. Such new capability should enable important advances in spray combustion research.

(d) System Improvements

A major activity during the past year has been to specify and to begin assembly of two second-generation solid-state camera systems and a facility for processing image data. In our early work on quantitative visualization we were forced to design and assemble a one-of-a-kind intensified camera and display system, using components drawn from a number of commercial sources and solving a number of interfacing and software problems on our own. This system was suitable for demonstrating feasibility of PLIF imaging in a variety of reacting flows, but it also had several deficiencies and was not well suited for adoption by user-oriented researchers interested in acquiring similar capability. With the award of a DOD equipment grant for 1984/85, we were able to begin to upgrade our system and to capitalize on the improved performance, availability and compatibility of commercial sub-systems.

A schematic diagram of our planned image acquisition and processing facility is shown in Fig. 4. Items not yet delivered or specified are indicated with asterisks. The facility will be housed in the High Temperature Gasdynamics Laboratory (HTGL) at Stanford with the VAX-750 located in the HTGL computer center and the three camera systems, located in separate laboratory rooms, linked via an Ethernet. The VAX-750 will also eventually be linked via Stanford's own network (S.U. Net) to other computers and image processing facilities on campus. We expect our facility to be fully operational in six months.

For purposes of this discussion, we consider the facility to consist of three components: detector arrays; dedicated microcomputers for camera control, data acquisition and preprocessing of data; and the central image processing computer. Key characteristics of these components and arguments for the specific items selected are given below.

The selection of the VAX-750 as the image processing computer was prompted primarily by arguments of cost, compatibility with other computers on campus, and availability of peripherals and software for

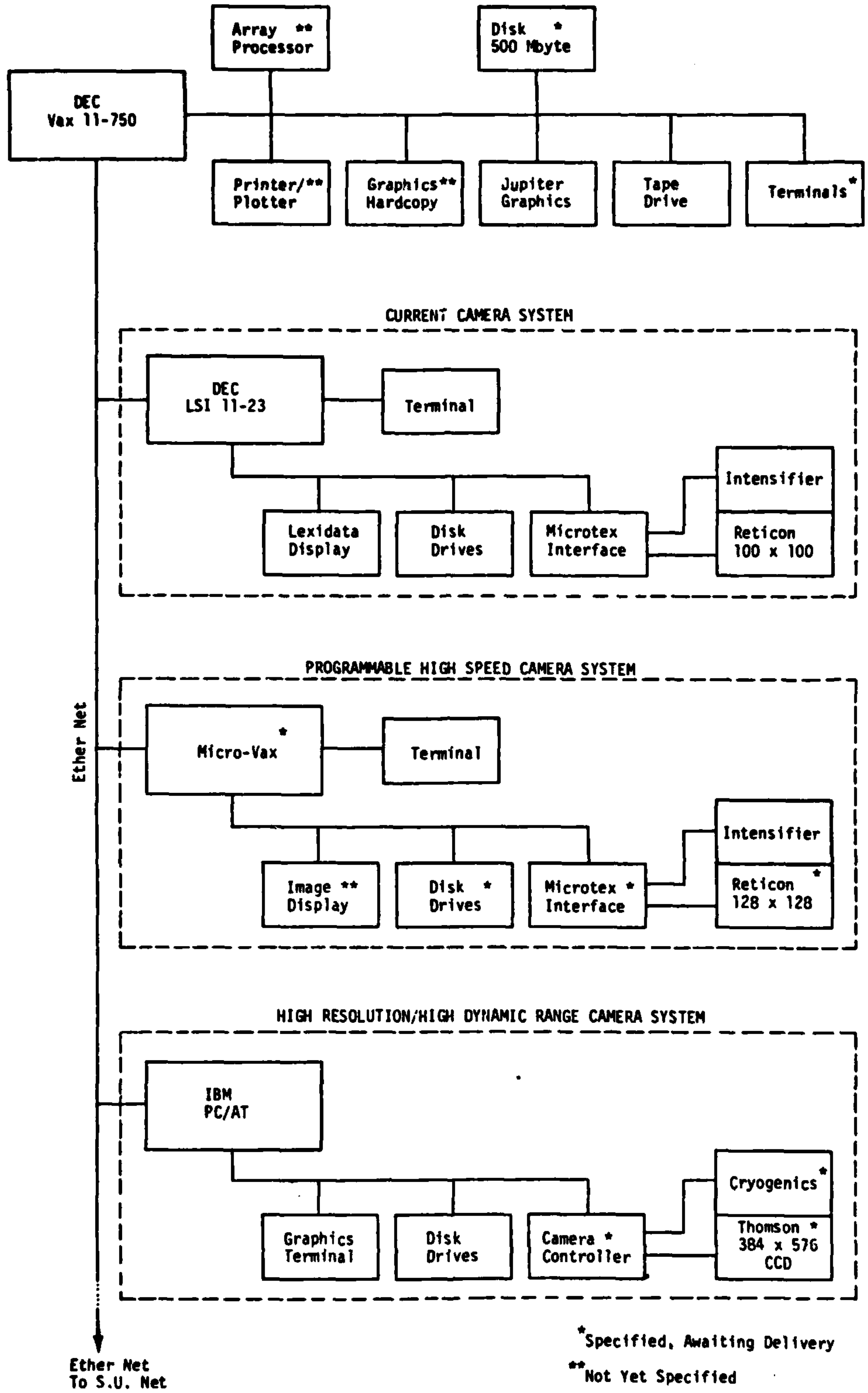

Fig. 1 Schematic diagram of image acquisition and processing facility.

Hanson, Paul & Kychakoff/Stanford University

image processing, display and output. We were able to acquire a complete new VAX-750 system for only $60,000, and to this we plan to add an array processor for fast, efficient processing of image data. The large number of VAX systems on campus including several used for image processing applications will result in shared expertise and software and a guaranteed connection to the S.U. Network. Other research groups active in combustion research and flow imaging, including nearby Sandia Laboratories (Livermore) also employ VAX systems, and we expect to benefit from exchanges of information and software from these groups as well.

Our goals for the solid-state cameras were to improve performance and ease of operation. Key performance parameters are noise level, spatial resolution and repetition (framing) rate. We opted for two separate systems, one with low noise and high spatial resolution, and one with programmable framing rate capability. (We call the former the High Resolution/High Dynamic Range System and the latter the Programmable High Speed System.) The virtues of the low noise system are evident in Fig. 5 which plots signal-to-noise ratio versus input photons per pixel (i.e., the "signal") for four separate arrays: intensified and unintensified Reticon arrays, [(100 x 100) or (128 x 128)], and two cooled CCD arrays (Thomson, 384 x 576), one with a standard amplifier and one with a special low-noise amplifier. The dashed line is the theoretical performance limit set by shot noise statistics. The right-hand boundary of the curves (at 2.5×10^5 photons/pixel for the Reticon array and 1.0×10^6 for the Thomson CCD array) are saturation levels beyond which the system becomes nonlinear.

We see that the High Resolution/High Dynamic Range System (based on the Thomson CCD with a "standard" amplifier) offers superior S/N over the Programmable High Speed System (based on an intensified Reticon 128 x 128) for light levels above 200 photons per pixel. The curves plotted are a reminder that if we seek a high S/N to enable detection of small changes in flowfield properties, it will be necessary to perform experiments with light levels near their saturation values. At saturation, the cooled CCD will yield a maximum S/N of 1000 while the intensified Reticon is limited to about 100. We regard this improvement as critical

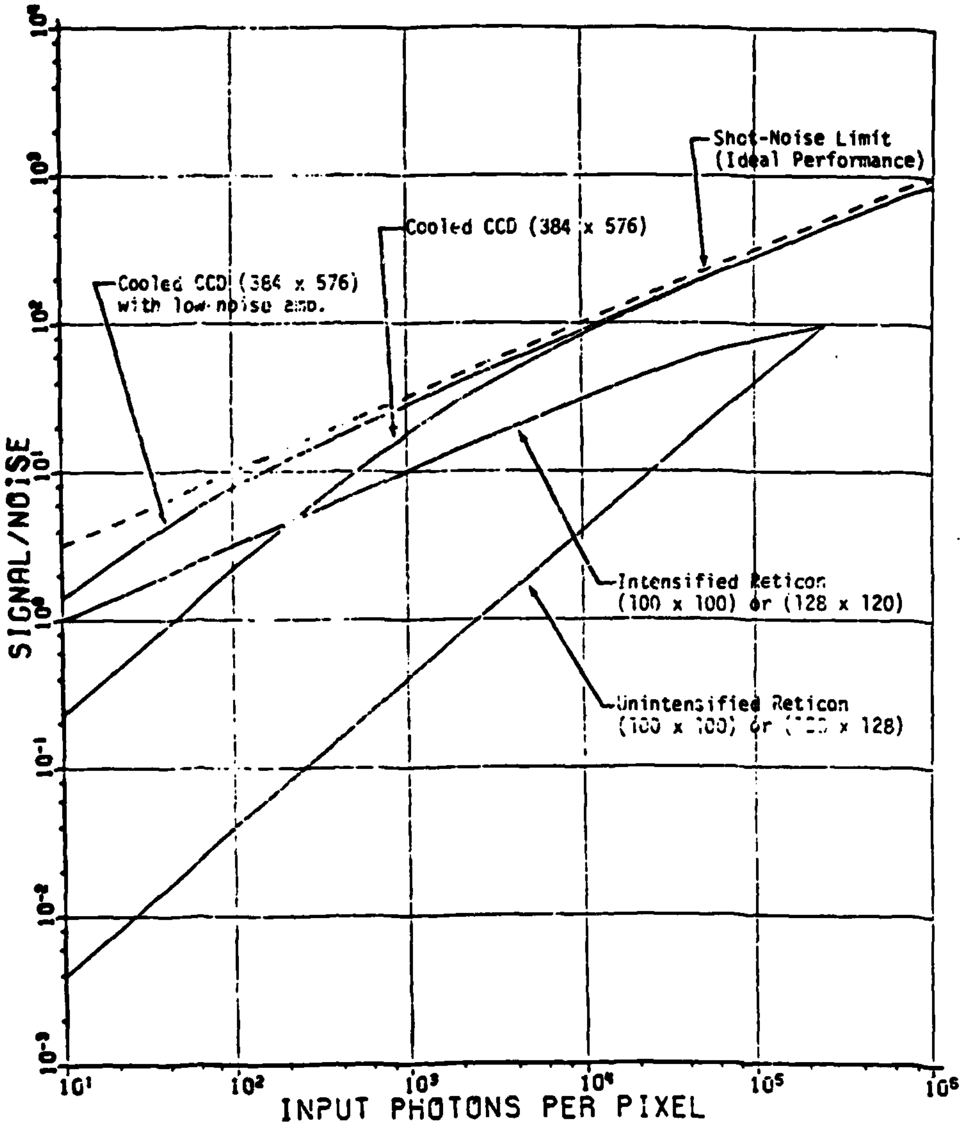

Fig. 2 Signal/noise ratio versus illumination (in photons/pixel) for four array cameras.

for many experiments, for example in turbulence studies where it may be essential to detect small changes in signal level. As can be seen in Fig. 5, the CCD system equipped with a custom low-noise amplifier actually outperforms the intensified Reticon at all light levels, and it is unintensified, which offers significant cost and operational advantages. The CCD array cryogenics system and camera controller have been ordered as a packaged system from Photometrics.

In addition to the S/N advantages of the CCD system, the array architecture and camera controller appear to offer important advantages for analog processing (averaging) of pixel groups, and "scrolling" and "tracking" of data between exposed and unexposed pixels for fast, burst-mode recording of multiple exposures on a single frame. (Actually, the architecture is a double array, 384 x 576 + 384 x 576, which provides capacity for "buffer" storage of data.) In contrasting a CCD-based system to an intensified Reticon system the primary disadvantages are: the need to interface the CCD camera to its dedicated microcomputer, since this has not been done previously; the lack of ultraviolet sensitivity with CCD detectors; and the low framing rate (~10 sec/frame) required to achieve ultra-low-noise performance with the CCD system. We are working together with Photometrics on the problem of interfacing the CCD camera to the IBM PC/AT microcomputer so that there is a good chance that our combined efforts will lead to a complete IBM PC/AT and cooled CCD system as a standard package from Photometrics. Such an off-the-shelf, modern and powerful system should be reasonably priced (no intensifier required; savings of $20,000) and would expedite adoption of quantitative flow visualization techniques by user-oriented groups. To provide the CCD system with ultraviolet viewing capability, we are investigating coating the detector with a material that absorbs ultraviolet radiation and reemits fluorescence radiation in the visible; such materials are known as "waveshifters".

Our decision to proceed in parallel with a programmable high-speed intensified Reticon camera (128 x 128) was based in part on our previous experience with such an array and the improved availability of packaged system components from Microtex, a vendor which has produced buffer

memory and camera controller system components for us in the past. Microtex now seeks to market a complete system (including everything in the dashed box in Fig. 4 labeled Programmable High Speed System), which relies heavily on our experience at Stanford. The system components we plan to acquire from Microtex are similar to those now on order by other groups at Volvo, UTRC, GM Research Labs and Yale University, and will enable programmable trade-offs between framing rate and the number of pixels up to a rate of 2 kHz.

Finally, with regard to the dedicated microcomputers for each camera, we've opted for the new DEC Micro-Vax with the Programmable High Speed System, since Microtex will be basing its newest system on that computer, and we've selected the IBM PC/AT because of its high performance/cost figure, the expected wide availability of peripherals and software for the machine, and our cooperation with Photometrics to develop a packaged, advanced performance camera system interfaced with the PC/AT.

Finally, we should note one other system improvement currently in progress, namely the installation and testing of our new 250 Hz excimer-pumped dye laser system which will serve as a high-repetition-rate source for imaging. We found that the laser system delivered met our specifications for power and repetition rate, but the beam quality was not suitable for laser sheet illumination work. Accordingly, we recently installed unstable resonator optics on the excimer, and this change seems to produce the desired uniform sheet beam. We anticipate the system will be fully operational within 60 days.

Publications and Presentations

Presentations

1. G. Kychakoff, K. Knapp, R.D. Howe and R.K. Hanson, "Quantitative Flow Visualization in Combustion Gases", paper No. 82-60, presented at Fall 1982 meeting, Western States Section/The Combustion Institute, Livermore, CA. (October 1982).

2. G. Kychakoff, R.D. Howe, R. K. Hanson and K. Knapp, "Flow Visualization in Combustion Gases," paper 83-0405, presented at AIAA 21st Aerospace Sciences Meeting, Reno (January 1983).

3. G. Kychakoff, R.D. Howe and R.K. Hanson, "Use of Planar Laser-Induced Fluorescence for the Study of Combustion Flowfields," paper 83-1361, presented at 19th Joint Propulsion Conference, Seattle (June 1983).

4. G. Kychakoff, R.D. Howe and R.K. Hanson, "Use of Planar Laser-Induced Fluorescence for Combustion Measurements," presented at CLEO '83, Baltimore (May 1983)

5. G. Kychakoff, R.D. Howe and R.K. Hanson, "Quantitative Flow Visualization Technique for Measurements in Combustion Gases," presented at the Ninth International Colloquium on the Dynamics of Explosions and Reactive Flows, Poitier, France (July 1983).

6. J.C. McDaniel and R.K. Hanson, "Quantitative Visualization of Flowfields Using Planar Laser-Induced Fluorescence," presented at International Flow Visualization Symposium, Michigan (September 1983).

7. R.K. Hanson, G. Kychakoff, E.C. Rea, Jr., B. Hiller, R.D. Howe and M.A. Kimball-Linne, "Advanced Diagnostics for Reacting Flows," presented at 20th JANNAF Combustion Meeting, Monterey, CA., October 1983.

8. R.K. Hanson, "Tunable Laser Absorption and Fluorescence Techniques for Combustion Research," invited paper presented at fall meeting of the APS, San Francisco, Nov. 21-23, 1983.

9. J.M. Seitzman, G. Kychakoff and R.K. Hanson, "Temperature Field Measurements in Combustion Gases Using Planar Laser-Induced Fluorescence," paper WF3 at CLEO '84, Anaheim, June 19-22, 1984.

10. J.M. Seitzman, G. Kychakoff and R.K. Hanson, "Temperature Field Measurements in Combustion Gases Using Planar Laser-Induced Fluorescence," paper 84-66 at Western States Section/The Combustion Institute, Stanford, Oct. 22-23, 1984.

11. R.K. Hanson, "Optical Imaging and Combustion Measurements," invited paper presented at Lasers '84, Symposium on Optical Imaging of Fluids, San Francisco, Nov. 26-30, 1984.

12. R.K. Hanson, M.Y. Louge, E.C. Rea, J.M. Seitzman and B. Hiller, "Recent Developments in Absorption and Fluorescence Laser Diagnostics for High Temperature Gases," invited paper presented at ICALEO '84, Laser Diagnostics and Photochemistry Symposium, Boston, Nov. 12-15, 1984.

13. R.K. Hanson, B. Hiller, E.C. Rea, Jr., J.M. Seitzman, G. Kychakoff and R.D. Howe, "Laser-Based Diagnostics for Flowfield Measurements,"

invited paper presented at Winter Annual Meeting of ASME, New Orleans, Dec. 9-14, 1984.

Publications

1. G. Kychakoff, R. D. Howe, R. K. Hanson and J. C. McDaniel, "Quantitative Visualization of Combustion Species in a Plane," Applied Optics 21, 3225 (1982).

2. G. Kychakoff, K. Knapp, R. D. Howe and R. K. Hanson, "Flow Visualization in Combustion Gases Using Nitric Oxide Fluorescence," AIAA J. 22, 153 (1984).

3. G. Kychakoff, R. D. Howe, R. K. Hanson, M. Drake, R. Pitz, M. Lapp, and M. Penney, "The Visualization of Turbulent Flame Fronts," Science 224, 382-384 (April 1984 issue; cover article).

4. G. Kychakoff, R.D. Howe, R.K. Hanson and K. Knapp, "Quantitative Visualization in Combustion Gases," AIAA Reprint 83-0405, 21st Aerospace Sciences Meeting, Reno, Jan. 10-13, 1983.

5. G. Kychakoff, R.D. Howe and R.K. Hanson, "Quantitative Flow Visualization Technique for Measurements in Combustion Gases," Applied Optics, 23 704-712 (1984).

6. G. Kychakoff, R.D. Howe and R.K. Hanson, "Use of Planar Laser-Induced Fluorescence for the Study of Combustion Flowfields," AIAA Reprint 83-1361, 19th Propulsion Conference, Seattle, June 27-29, 1983.

7. R.K. Hanson, G. Kychakoff, E.C. Rea, Jr., B. Hiller, R.D. Howe and M.A. Kimball-Linne, "Advanced Diagnostics for Reacting Flows," in Proceedings of 20th JANNAF Combustion Meeting, Monterey, CA., October 1983.

8. J.C. McDaniel and R.K. Hanson, "Quantitative Visualization of Flowfields Using Laser-Induced Fluorescence," in Proceedings of 3rd International Flow Visualization Symposium, Univ. of Michigan, September 1983.

9. G. Kychakoff, R.K. Hanson and R.D. Howe, "Simultaneous Multiple-Point Measurements of OH in Combustion Gases Using Planar Laser-Induced Fluorescence," 20th Symposium (International) on Combustion, The Combustion Institute, in press.

10. R.K. Hanson, B. Hiller, E.C. Rea, Jr., J.M. Seitzman, G. Kychakoff and R.D. Howe, "Laser-Based Diagnostics for Flowfield Measurements," Amer. Soc. Mech. Eng. AMD-Vol. 66, pp. 1-10, 1984.

11. R.K. Hanson, M.Y. Louge, E.C. Rea, J.M. Seitzman and B. Hiller, "Recent Developments in Absorption and Fluorescence Laser Daignostics for High Temperature Gases," to be published in Proceedings of

ICALEO '84, Laser Diagnostics and Photochemistry Symposium, Boston, Nov. 12-15, 1984.

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Robert Howe	Graduate Student, Mechanical Engineering
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2.4 Velocity Visualization

Introduction

Velocity measurements provide essential input for many fundamental and applied fluid mechanics studies. At present, hot wire anemometry and laser Doppler anemometry are the most commonly used techniques. Both methods have advantages and disadvantages, but in particular they are single-point diagnostics. Clearly, a technique yielding simultaneous multiple-point velocity data would represent a significant diagnostics contribution and could stimulate important advances in many areas involving fluid flow.

Our effort in this area was prompted in part by our success in visualizing species at multiple points in a flow (see Section 2.3) and the growing recognition that combinations of flowfield quantities (e.g., species, temperature, pressure and velocity) may eventually be needed to test advanced flow models. Accordingly, in 1982 we initiated a new effort to "visualize velocity", i.e. to measure velocity at a large number of spatially resolved flowfield points leading to a computer display of velocity.

During this reporting period, work has proceeded on two schemes. The first method is based on the Doppler effect and involves monitoring the broadband fluorescence from a sheet-illuminated flow using a Reticon array. The flow is seeded with a tracer species and a narrow-linewidth laser source is used to excite a specific wavelength within a single absorption line of the tracer species. The fluorescence from a given flowfield point mirrors the absorption occurring there, which for a uniformly seeded flow may depend primarily on the position of the laser wavelength within the absorption lineshape. Since the apparent laser frequency shifts with fluid velocity due to the Doppler effect, the amount of absorption (and hence fluorescence) is a measure of velocity.

The second scheme, which has been investigated just recently, involves "marking" specific elements of the flow using laser-excited phosphorescence. Subsequent motion of the marked elements is observed on our intensified photodiode array. A variation of this scheme involving laser-induced formation of particulates (which can be tracked by Mie scattering) has also been investigated.

Scientific Merit

The importance of velocity as a fluid flow parameter is obvious, and so the discovery/establishment of an improved velocity diagnostic offers broad potential for improved scientific understanding of fluid flows. A successful multiple-point diagnostic, in particular, would represent a sufficiently large advance in measurement capability as to enable first-time observations of various flow phenomena and possible discovery of unexpected features.

One of the techniques proposed, based on the velocity modulation (Doppler shift) of molecular absorption lines, offers prospects for a significant improvement over conventional laser Doppler (particle seeding) anemometry for supersonic flows, flows near surfaces (boundary layers) and flows with high acceleration or deceleration where particle lag is a serious problem. Furthermore, multiple-point recording of velocity, and subsequent evaluation of velocity gradients, offers prospects of yielding images of vorticity, a fundamental flowfield variable of growing importance in current fluid meachanics modeling.

Status Report

This research is still in its early stages. We have conceived and investigated several promising approaches for multiple-point velocity measurements, and we have selected two of these approaches, Doppler-shifted absorption and laser marking, for laboratory study.

The strategy of the velocity-modulated molecular absorption technique is based on detection of fluorescence from a Doppler-shifted absorption line of a tracer species excited by a narrow-linewidth laser source. Iodine (I_2) vapor has been used in the work thus far (because it conveniently absorbs the light at visible wavelengths of tunable Ar^+ and cw dye lasers), although the method is quite general. Velocity measurements in I_2-seeded, low temperature flows have now been demonstrated for both supersonic and subsonic cases, using somewhat different procedures. Details of the apparatus, procedures and results are available in publications 1,2,5,6 and 7 cited below.

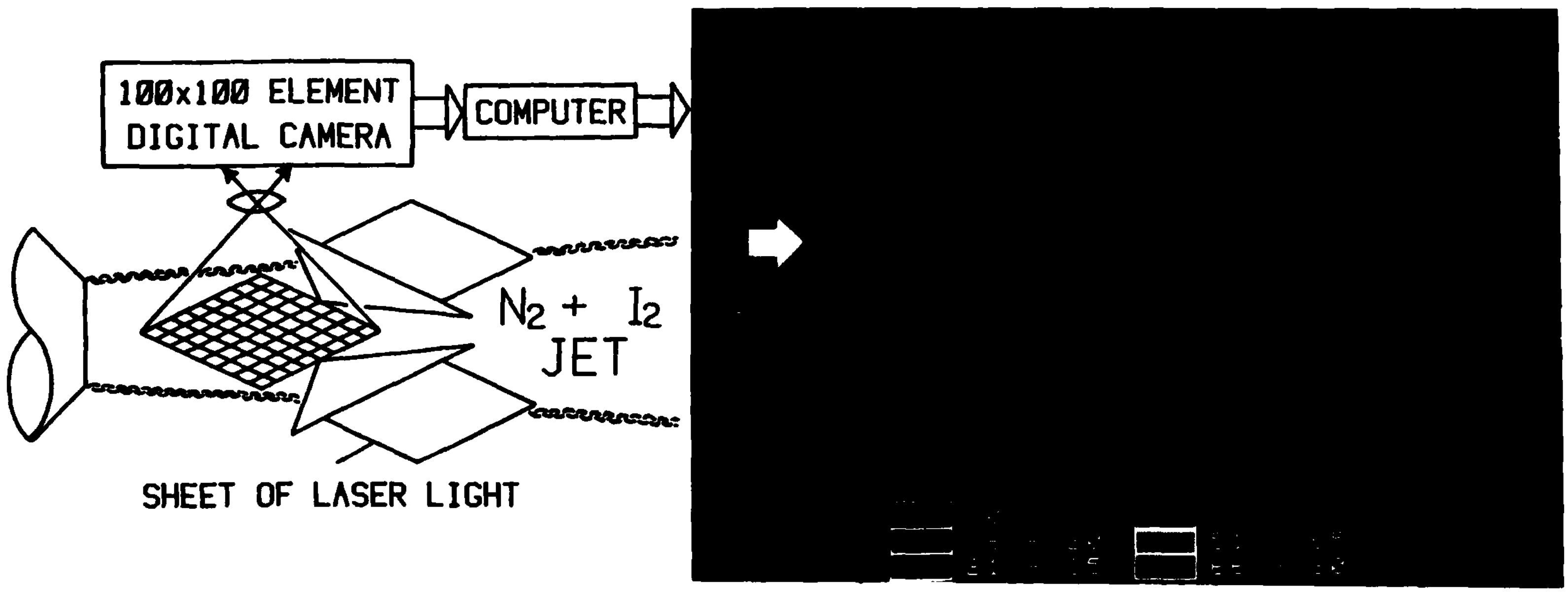
A sketch of the arrangement and typical results for velocity in the centerplane of a subsonic nitrogen round jet are shown in Fig. 1. I_2 is seeded into the flow at a trace level of about 300 ppm. A sheet of cw single mode Ar^+-laser light, tuned to a frequency in the wing of the overlapping P(13)/R(15) lines of I_2 ((43,0) band at 514.5 nm), is incident at an angle of 45° to the jet centerline. An intensified photodiode array (100 x 100) camera, imaging the plane of illumination, records the broadband fluorescence emanating from each of the 10^4 imaged locations. The fluorescence signal from each point is proportional to the amount of light absorbed at that point, which in turn depends on the extent of the local velocity-induced Doppler shift of the absorption line relative to the fixed laser frequency (see Fig. 2).

In our initial work, we utilized a single laser frequency and two angles of illumination (to determine two independent velocity components), but recently we have implemented an important improvement based on a two-frequency strategy (see Fig. 2). In brief, we utilize an acousto-optic device to convert the single-mode laser output to two discrete laser frequencies separated by 100 MHz. With this scheme, simple differences in the signals from forward and counterpropagating sheets (at a single angle), normalized by the difference in the mean (unshifted) signals at the two frequencies, leads directly to the velocity component for that angle. This scheme is self-calibrating and eliminates the previous requirement to know (by external calibrations) the absorption lineshape function. Details of this improved approach are given in a recent paper (number 5 on the list below).

The present scheme thus uses four camera frames, one for each of four sheets of light, i.e. forward and counterpropagating sheets at each of two angles (± 45° relative to the jet axis) in the centerplane, to allow determination of the velocity vector in the centerplane of the flow. Although the time required to complete the four measurements was about 0.4 seconds in these experiments, much shorter measurement times are feasible. The sensitivity of the method, currently a few m/s, indicates the capability of the 4-beam technique to probe a variety of low and high Mach number flowfields. The simplicity of the scheme should

2-D Velocity Measurement

- SPATIAL VELOCITY DISTRIBUTIONS VISUALIZED WITH LASER-INDUCED FLUORESCENCE

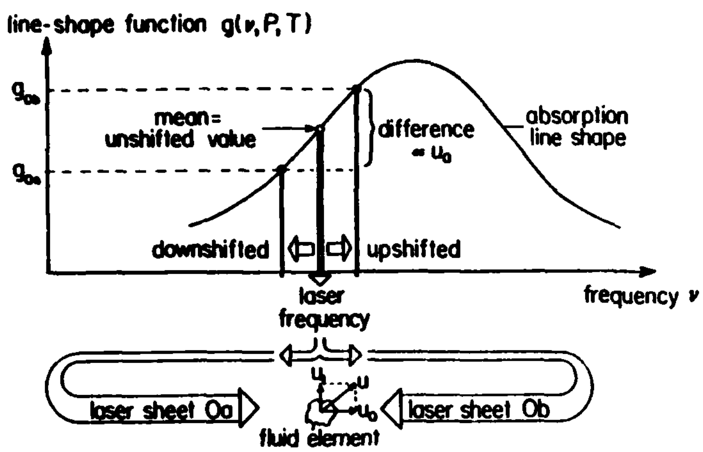


- NOVEL TWO-FREQUENCY TECHNIQUE IS SELF-CALIBRATING
- NO PARTICLE SEEDING REQUIRED
- FAST DATA PROCESSING; PROSPECTIVE TECHNIQUE FOR REAL-TIME MONITOR
- SENSITIVITY DEMONSTRATED TO 5 m/s; ACCURACY IMPROVES WITH INCREASING VELOCITY
- POTENTIAL FOR COMBINED VELOCITY AND PRESSURE MEASUREMENTS

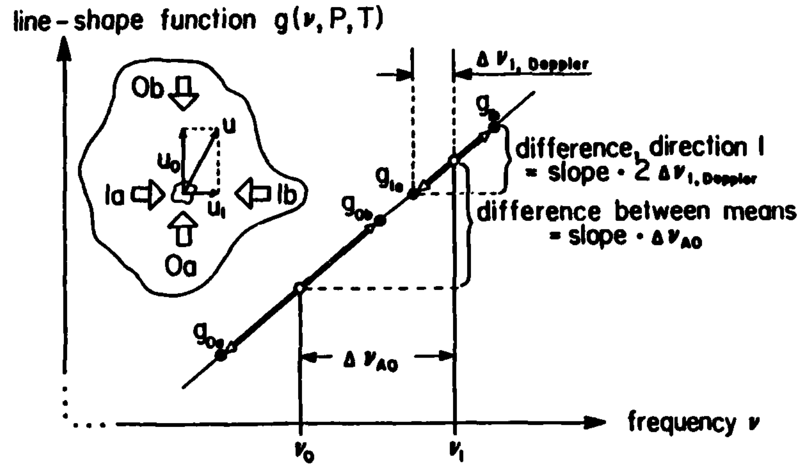
Fig. 1 Approach and results for velocity visualization technique.

Hanson & Hiller/Stanford Univ.

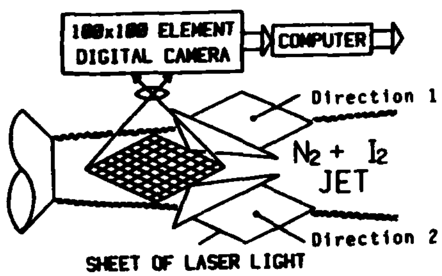
TWO-FREQUENCY STRATEGY FOR VELOCITY VISUALIZATION

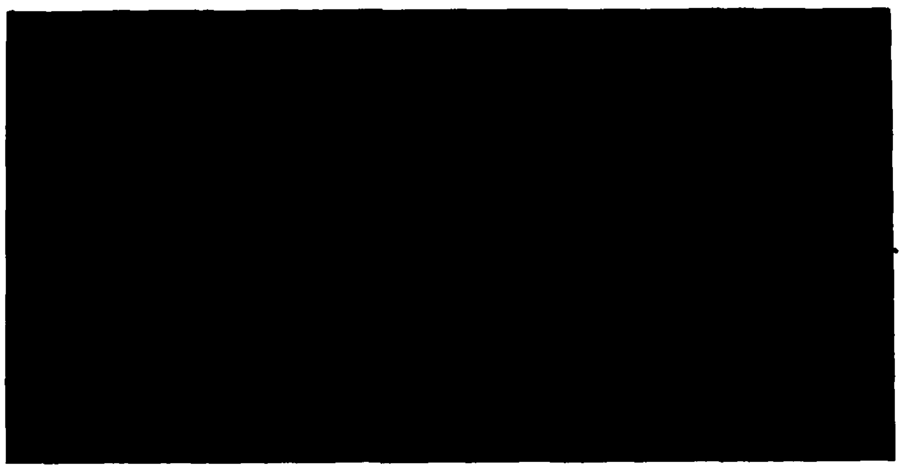


Effect of Doppler-Shift on Absorption
Line-Shape Function: Single Frequency



Two Laser Frequencies: Ratio of Differences
Provides Self-Calibrated Velocity Measurement





Data for Subsonic Roundjet

Fig. 2 Two-frequency strategy for velocity visualization and typical data for velocity components in a subsonic roundjet.

lend itself to fast on-line data processing. The excellent spatial resolution which can be achieved is an intrinsic feature of laser-induced fluorescence techniques. Further improvements are being directed toward simplifying the experimental set-up, improving temporal resolution, and developing a strategy for simultaneously inferring pressure from the two-frequency velocity data. Experiments in combusting flows using naturally occurring or seeded species are also planned.

With regard to our second velocity project, utilizing laser marking, an initial series of feasibility experiments using laser-induced phosphorescence has been successfully completed (see Fig. 3). The seed material used was biacetyl (also known as 2,3-butanedione), which has a conveniently large vapor pressure (about 40 torr at room temperature) and readily separated fluorescence (short-lived) and phosphorescence (long-lived) emission spectra. A schematic diagram of the set-up and sample results for flow through a slot are given in Fig. 3. Details are available in our recently submitted paper (see number 3 in the publication list below). A variation of this scheme involving laser-induced formation of particulates (which can be tracked by Mie scattering) has also been investigated. Details of that work, using sulfur hexafluoride (SF_6) with excitation by Nd:YAG at 1.06 μm, have also been published (see paper 4 below).

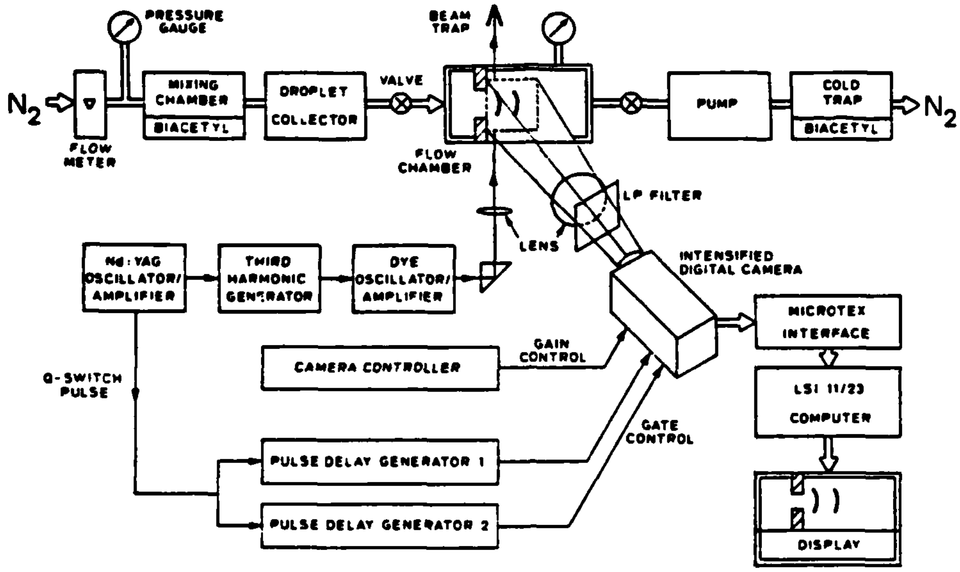
Publications and Presentations

Presentations

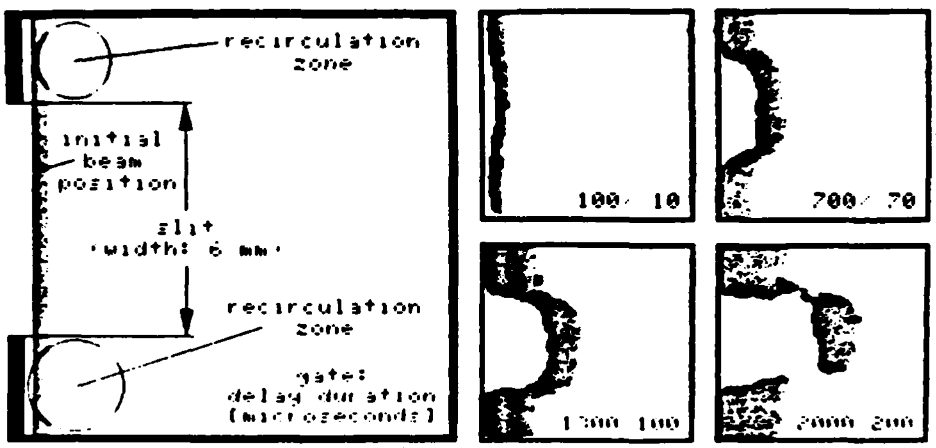
1. J.C. McDaniel, "Velocity Measurements Using Doppler-Shifted Laser-Induced Iodine Fluorescence," presented at Thirty-Fifth Meeting of the American Physical Society, Div. of Fluid Dynamics, Rutgers U., Nov. (1982).

2. J.C. McDaniel, "Quantitative Measurement of Density and Velocity in Compressible Flows Using Laser-Induced Iodine Fluorescence," paper 83-0049 presented at AIAA 21st Aerospace Sciences Meeting, Reno (January 1983).

3. B. Hiller, J.C. McDaniel, E.C. Rea, Jr., and R.K. Hanson, "Laser-Induced Fluorescence Technique for Velocity Measurements in Subsonic Flows," presented at CLEO '83, Baltimore (May 1983).



(a)



(b)

Fig. 3. (a) Setup picture showing flow path, optical path and electronics for laser marking experiment using laser-induced phosphorescence of biactyl.

(b) Single-pulse picture series of the two-dimensional flow through a slit for different gate delay/duration times. The Reynolds number based on slit width is Re = 900.

4. B. Hiller and R.K. Hanson, "Laser-Induced Fluorescence Technique for Velocity Field Measurements in Compressible Flows," presented at the Thirty-Sixth Annual Meeting of the American Physical Society, Div. of Fluid Dynamics, Houston, Nov. (1983).

5. R.K. Hanson, M.Y. Louge, E.C. Rea, J.M. Seitzman and B. Hiller, "Recent Developments in Absorption and Fluorescence Laser Diagnostics for High Temperature Gases," Presented at ICALEO '84, Laser Diagnostics and Photochemistry Symposium, Boston, Nov. 12-15, 1984.

6. R.K. Hanson, B. Hiller, E.C. Rea, Jr., J.M. Seitzman, G. Kychakoff and R.D. Howe, "Laser-Based Diagnostics for Flowfield Measurements," invited paper presented at Winter Annual Meeting of ASME, New Orleans, Dec. 9-14, 1984.

7. R. Hanson, "Optical Imaging and Combustion Measurements," invited paper presented at Lasers '84, Symposium on Imaging of Fluids, San Francisco, Nov. 26-30, 1984.

Publications

1. J.C. McDaniel, B. Hiller and R.K. Hanson, "Simultaneous Multiple-Point Velocity Measurements Using Laser-Induced Fluorescence," Optics Letters 8, 51 (1983).

2. B. Hiller, J.C. McDaniel, E.C. Rea, Jr., and R.K. Hanson, "Laser-Induced Fluorescence Technique for Velocity Measurements in Subsonic Flows," Optics Letters 8, 474 (1983).

3. B. Hiller, R.B. Booman, C. Hassa and R.K. Hanson, "Velocity Visualization in Gas Flows Using Laser-Induced Phosphorescence of Biacetyl," Review of Scientific Instruments, in press.

4. C. Hassa and R.K. Hanson, "Fast Laser-Induced Aerosol Formation for Visualization of Gas Flows," Rev. of Sci. Inst., submitted Oct. 1984.

5. B. Hiller and R.K. Hanson, "Two-Frequency Laser-Induced Fluorescence Technique for Rapid Velocity Field Measurements in Gas Flows," Optics Letters, submitted for publication, Dec. 1984.

6. R.K. Hanson, M.Y. Louge, E.C. Rea, J.M. Seitzman and B. Hiller, "Recent Developments in Absorption and Fluorescence Laser Diagnostics for High Temperature Gases," to be published in Proceedings of ICALEO '84, Laser Diagnostics and Photochemistry Symposium, Boston, Nov. 12-15, 1984.

7. R.K. Hanson, B. Hiller, E.C. Rea, Jr., J.M. Seitzman, G. Kychakoff and R.D. Howe, "Laser-Based Diagnostics for Flowfield Measurements," Amer. Soc. Mech. Eng. AMD-Vol. 66, pp 1-10 (1984).

Personnel

Ronald K. Hanson	Professor, Mechanical Engineering
Bernhard Hiller	Graduate Student, Mechanical Engineering (Ph.D. expected December 1985).
Chris Hassa	Graduate Student, Mechanical Engineering
Larry Cohen	Graduate Student, Mechanical Engineering
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2.5 Plasma Diagnostics for Energy Conversion Research

Introduction

An emerging element of our overall program is research on plasma diagnostics which will be of subsequent use in fundamental research on plasmas and in studies of various plasma-related energy conversion schemes.

Primary motivation for this work arises from renewed interest in advanced space power and propulsion systems which may involve plasmas. Among the systems under consideration are thermionic converters and MHD generators for electrical power generation, MPD thrusters and beamed laser energy for propulsion, and direct production (in space) of high-power laser radiation for beamed energy. Considerable research will of course be needed before optimum systems for space utilization are identified, developed and placed in service, and we believe that advanced diagnostics can play an important role in such research. Furthermore, the initiation of work on plasma diagnostics forms a logical, efficient extension of our current program.

Scientific Merit

This research seeks to provide new diagnostic methods for use in studies of plasma properties and plasma phenomena. The merit of our work rests on the growing significance of plasma sciences in connection with Air Force activities and interests, and also on the critical role which advanced diagnostics can play in facilitating basic and applied research in this area. The techniques which we plan to pursue are novel and offer potential for significantly enhancing diagnostics capabilities in ionized gases. We intend to coordinate this work closely with other OSR-sponsored work on plasma sciences underway in our laboratory, and we expect the scientific merit and relevance of the work to be enhanced by these interactions.

Status Report

This research is still in an early stage and our work has consisted primarily of literature reviews, paper studies of candidate diagnostic techniques and plasma facility assembly. On the basis of this background work, we have narrowed our selection of diagnostics topics to three rather broad areas: (1) quantitative visualization of plasmas using PLIF, i.e. simultaneous multiple-point laser-induced fluorescence measurements or imaging of plasma parameters such as species concentration (including ions and electrons), temperature and electric field strength; (2) wavelength modulation spectroscopy using laser absorption and/or fluorescence; and (3) other laser scattering concepts. To put our work in focus, we are particularly interested in techniques which have promise for measurements with high spatial resolution, for example near electrodes and boundaries where discharge and erosion phenomena are of importance, and in finding new, improved methods for quantities such as temperature, electron number density, ion species concentrations and electric field strength.

A block diagram indicating the laser systems to be employed, the techniques of interest, and the plasma systems to be studied, is given in Fig. 1. Two of the three laser systems indicated, providing tunable cw dye laser radiation (280-700 nm, with some gaps) and tunable pulsed dye laser radiation (220-900 nm), are already on hand. We also hope to provide new capability to access tunable vacuum ultraviolet (VUV) wavelengths by adding a Raman shifter (cell of H_2 at high pressure) to our pulsed dye laser. This addition, to be proposed for FY 86, will allow access to the absorption/fluorescence spectra of a variety of atomic species of importance in plasma and electrode phenomena studies.

We plan to conduct research in two widely separate plasma regimes: low-pressure discharges (probably RF powered) and high-pressure arcs (using induction heating). The low pressure facility is now complete except for the power supply. In brief, the viewing chamber is a stainless steel box, with windows on all four sides, and electrodes mounted on removable top and bottom plates. The chamber is coupled to an inlet gas manifold, for varying the input gas composition and flow rate,

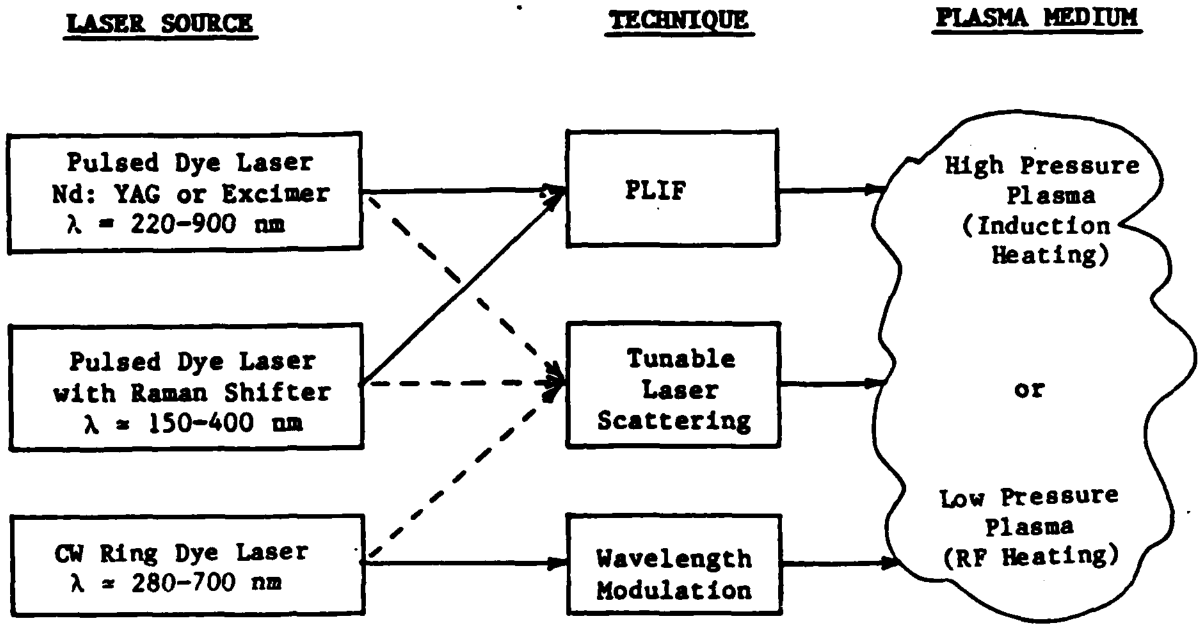

Fig. 1 Laser Systems and Techniques for Plasma Diagnostics Research.

and to a vacuum pump. We have paid particular attention to optical access so that we will be able to demonstrate the ability to measure with high spatial resolution near surfaces (electrodes) and with high temporal resolution in transient discharges.

With regard to the high-pressure facility, we were fortunate to be able to recently acquire (on surplus; shipping costs only) two high-power (25 and 50 kW) induction-heating power supplies. These systems, which are currently being installed in our laboratory, will provide nearly ideal capability for diagnostics studies and, subsequently, research on a variety of plasma sciences topics (e.g., plasma processing, for powders and gases; laser-plasma interactions and energy transfer; and non-equilibrium aspects of plasmas). Important advantages of induction-heated plasma production are: the convenient optical access, the wide range of allowed plasma materials, and the absence of contaminating electrodes. A schematic diagram of the induction-heated plasma torch, listing some of the key features, is presented in Fig. 2.

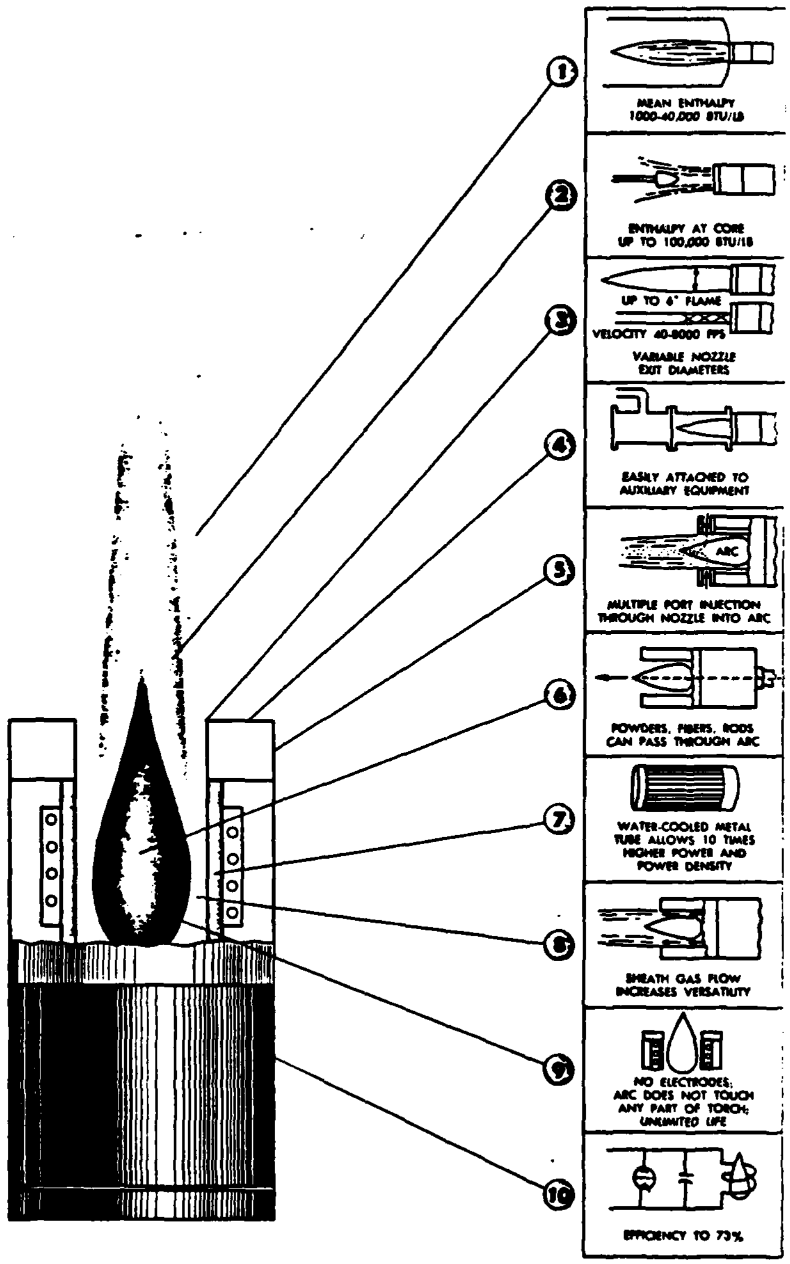

Fig. 2 Some key features of induction-heated plasma torch.

The status of our work on diagnostics is that we have reviewed a variety of candidate measurement ideas, leading to the three categories of techniques noted above, and have decided to proceed initially with category (1), namely planar laser-induced fluorescence (PLIF) plasma measurements. Once our plasma torch is functional, we plan to set-up a PLIF system and establish procedures for monitoring the properties of interest: ion concentrations, temperature and electron number density. As an example, our plan for electron density (n_e) is to make use of the known relationship between the Stark-broadened absorption lineshape function and n_e. We intend to excite two different wavelengths within a specific absorption line, and to use the ratio of the two resulting LIF signals (at each flowfield point or pixel) to establish n_e. Some calculations to select optimum wavelength positions within a line, and to select suitable species and transitions, will be needed to guide the experiments. In most respects, the experimental PLIF arrangement will be similar to that employed in our combustion research.

There is of course a requirement to match the wavelengths of the exciting laser system with the absorption spectra of molecules of interest, and so our initial experiments will be influenced by the tunable laser sources currently in our laboratory. More specifically, we plan to utilize both our tunable cw dye laser (which can provide narrow-linewidth output in the ranges λ = 280-310 nm, 340-345 nm and about 500-700 nm) and our tunable pulsed dye laser (broadband output in the range λ = 220-900 nm) as laser sources in PLIF experiments. In addition, we hope to acquire a Raman shifter, to be pumped by either our pulsed dye laser or our excimer laser itself, which will provide access to wavelengths in the VUV. A curve based on preliminary calculations of output pulse energy versus wavelength is shown in Fig. 3. Note that we expect to be able to reach all wavelengths down to about 160 nm with a pulse energy of at least 1 microjoule. Using fixed-frequency excimer lines we can generate higher pulse energies at discrete wavelengths. The values shown correspond to the specifications of our excimer and excimer-pumped dye laser. We are presently carrying out a survey of absorption spectra of relevant compounds which fall in this spectral region. Further literature searches regarding spectra of relevant atoms and molecules will be carried out as part of this research.

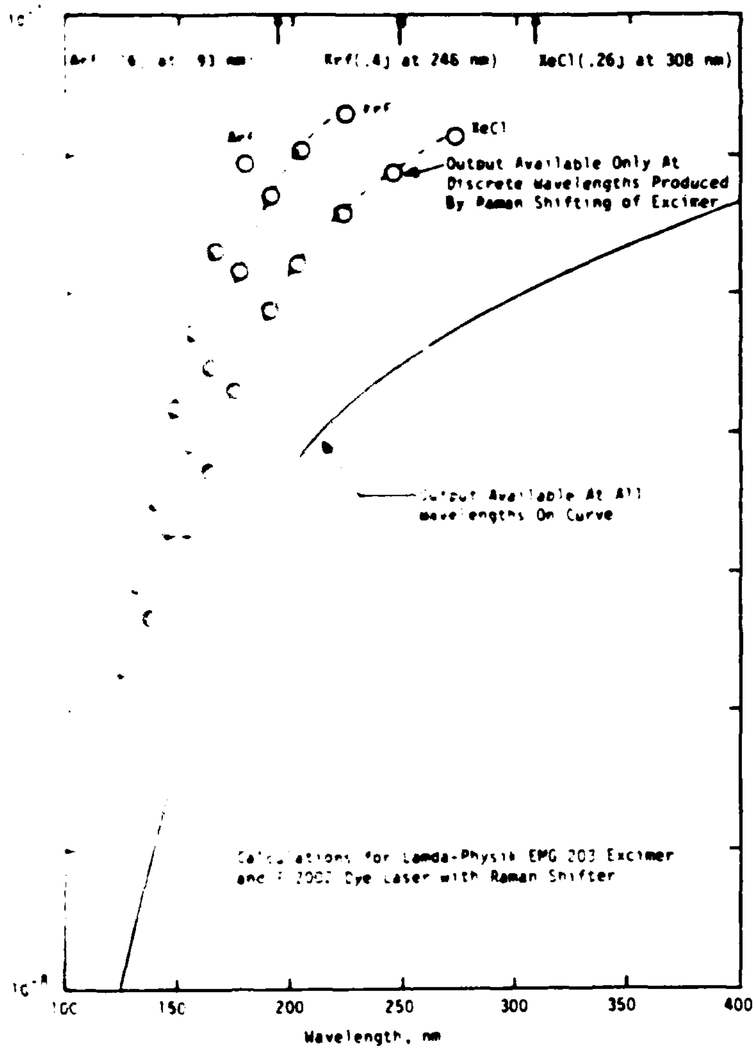

Fig. 3 Output energy per pulse for: discrete wavelengths produced by Raman shifting EMG 203 excimer laser; and continuous wavelengths produced by Raman shifting F2002 pulsed dye laser.

The second category of techniques to be explored is wavelength modulation spectroscopy. Our ideas here are not yet well defined, but in brief we wish to explore the utility, for plasmas, of the same approaches we are currently establishing for combustion measurements. The wavelength region we can access with our fast-tuning cw laser system

is somewhat limited, and so one of our first activities is to become more familiar with the absorption/fluorescence spectra of the species accessible in our plasma torch or low pressure plasma facilties. Once these plasma facilities are operational, we will conduct an absorption-based spectral survey of the plasma to identify suitable spectral features which can be used in our work to establish measurement strategies. Our hope is that fully resolved fluorescence measurements will yield, through the apparent linewidths or line shifts, information on plasma properties such as electron concentration or temperature, in addition to the local species concentration for the absorbing species.

Finally, and on a more speculative basis, we wish to explore laser-based scattering techniques for plasma measurements. As a first example, we would like to pursue a novel concept for determining the electron number density via measurements of the plasma frequency, the latter being a characteristic local frequency of the plasma which is a known funciton of the electron number density. Our idea, which is untested, is to cross two lasers at a point, and to vary the laser frequency difference until it matches the plasma frequency. At this point the plasma will be excited and should exhibit, we hope, enhanced scattering of light at one of the incident wavelengths. The scattered light, present only when the separation in laser frequencies matches the plasma frequency, is simply an indicator of when the matching conditions is satisfied. The frequency itself will be inferred from simple etalon traces of the laser and hence should be very precise. Although this idea is in a very preliminary stage, it illustrates the type of new approach we would like to take in this work.

One further preliminary idea regarding PLIF plans for plasmas should be mentioned, and that has to do with growing interest in radiative coupling between lasers and plasmas, i.e. laser-sustained or stimulated plasmas. As an example, UV lasers are now being used to selectively influence plasma chemistry, particularly in connection with chemical vapor deposition on surfaces. Once our high-repetition-rate excimer laser is installed as planned for our flow visualization work in combustion gases, this laser could also serve as a high power source of UV

radiation to initiate or perturb a plasma, the behavior or response of which could then be studied using our PLIF plasma diagnostics system. Working in such an area, namely laser-plasma interactions (including chemistry and energy conversion topics), would provide useful focus for our diagnostic research and also increase both the visibility and potential scientific impact of our plasma-related program.

Publications and Presentations

None

Personnel

Ronald K. Hanson	Professor, Mechanical Engineering
Phillip Paul	Research Associate, Mechanical Engineering
Jerry Seitzman	Graduate Student, Mechanical Engineering (Ph.D. expected in June 1987)
Doug Baer	Graduate Student, Mechanical Engineering

2.6 OPTICAL PROCESSING AND PHASE CONJUGATION

I OBJECTIVE

The objective of the research program is to investigate innovative new approaches for making quantitative 3-D measurements in combusting flows. The techniques under investigation include optical and digital image processing, holography and phase conjugation.

II. INTRODUCTION

Turbulent combusting flows are complex, three-dimensional time-dependent phenomena. Diagnostic, nonintrusive optical techniques used to further expand our knowledge of these flows are usually sophisticated and computer based to accommodate the often enormous data throughput required. Recent work in the diagnostics area has been concentrated on planar measurements of such variables as velocity, density and species concentration. By properly scanning the laser sheet volumetric information can be obtained and we have investigated a novel technique for processing and display of these three-dimensional data fields using both video based and holographic techniques. The method investigated has widespread applications both in combusting and noncombusting flows. However, we found that conventional image processing techniques are not always applicable to combusting flow data. For example, edge finding techniques do not work very well when dealing with concentration data of particles or species due to extensive mass diffusion which tends to blur interfaces. Thus to present and process these data we needed to develop software custom tailored for these applications.(Ref 1)

From this work it has become clear that data acquisition is a major problem that needs to be examined carefully. For instance, sheet illumination techniques combined with reticon arrays are now limited to framing rates of approximately 500 pictures per second (100 x 100 arrays), the limiting factor being electronic data transfer. Thus, it appears of interest to investigate alternative approaches which may incorporate optical pre-processing or storage. In this report we discuss three new techniques. First, we will describe progress made in the area of three-dimensional processing and display of data. Secondly, we will describe a novel optical technique for making density measurements in a flame. The technique is based on optical phase conjugation and we report the first species concentration measurements in a flame using this technique. Thirdly, we will discuss progress made in the area of real-time speckle interferometry. The last project is a new start and was proposed for commencement in the 1984-1985 research year, but we have been able to get started ahead of schedule during the summer of 1984.

II. Three-dimensional flow visualization

The technique for obtaining a three-dimensional representation of a fluid flow from a stack of planar cross-sections has been described in a previous progress report and is not repeated here. We have continued our effort in the area of three-dimensional flow visualization using complicated new image processing techniques. In particular we have investigated the usefulness of the technique for combustion and fluid mechanics experiments. For this purpose we have studied the three-dimensional structure of a coflowing jet without combustion, a laminar premixed flame and a boundary layer flow. The boundary layer data are derived

from numerical calculations as opposed to experiments. The results of this investigation for the coflowing jet and the flame are described in paper 3. As an example, a video stereo pair of the coflowing jet is shown in figure 1. The top pairs represent a low Reynolds number flow, approximately Re=800, and the bottom flow corresponds to a Reynolds number of approximately 2000. It is interesting to note the pronounced three-dimensional structure which develops in the higher Reynolds number case and which cannot be easily detected by conventional two-dimensional techniques. The stereo pairs presented in figure 1 can be viewed by using an ordinary stereo viewer.

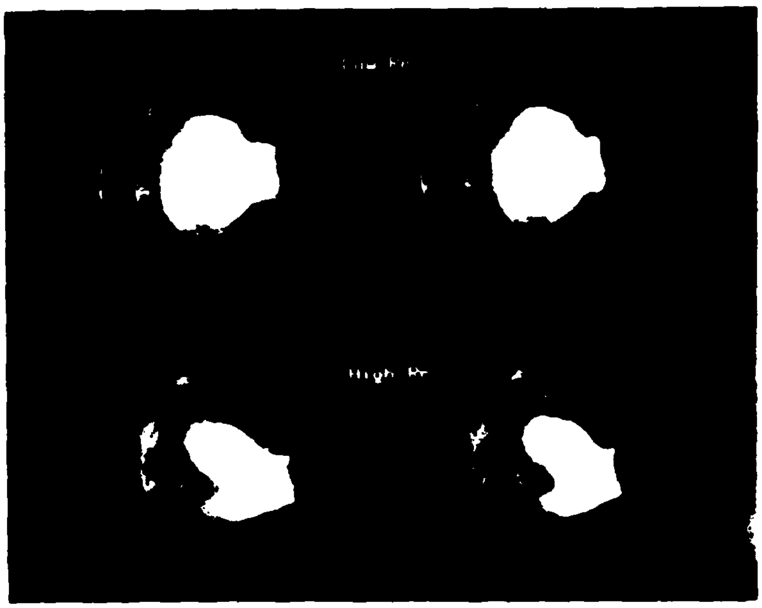

Figure 1. Stereo pairs of a coflowing jet

III. Phase conjugation in combusting flows

This effort is an extension of work which has begun at the end of the previous contract year (Spring 1984). Two counter propagating laser beams (or sheets) are incident on a flame seeded with sodium, and a third probe beam

intersects the other two. The probe and pump beam 1 form a grating in the medium by modulating the index-of-refraction through a nonlinear χ^3 process. The second pump beam is used to read out the hologram in real time and a fourth counter-propagating or phase conjugate probe beam results. The intensity of this beam is directly proportional to the local number density and thus provides a means for measuring species concentration. As an example we have discussed sodium, but reaction species and radicals can be measured in the same fashion as well. This technique has been used with pure sodium vapor before, but never in a combusting environment.

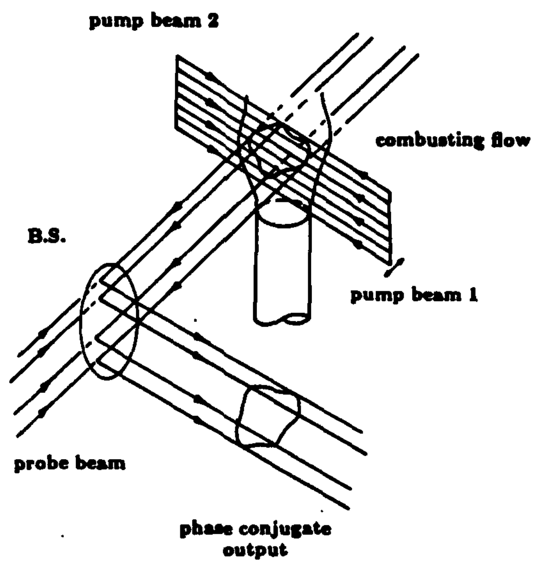

Figure 2. Phase conjugation in a flame

Combustion or heat release complicates the four-wave mixing process, because distortions in the phase fronts of the two counterpropagating pump beams may result. If these phase perturbations become too large, no phase conjugating beam will result, even although the material responds on a time scale

of less than nanoseconds. We have investigated this phenomenon during the past contract year. The potential of this new technique is substantial, because signal strength is relatively large and quenching problems are not impeding quantitative data interpretation as is often the case in laser induced fluorescence. The presence of heat release also influences the obtainable S/N ratio as well as the sensitivity of the technique. Thus these fundamental, combustion specific, issues need to be investigated. In addition to the already mentioned features of the technique it is also possible to perform optical data processing on the probe beam. By tuning the ratio of the probe-to-pump beam intensity it is possible to perform edge detection operations and thus data compaction which allows improved time resolution for a given data acquisition rate.

3.1 Progress

Last winter we started an investigation into the potential of some new materials for use as a phase conjugating medium via a third-order susceptibility; this research produced several possible candidates. Media in which one tunes close to an isolated resonance are most promising because of the high diffraction efficiencies attainable for a given amount of laser power. Examples of materials in which this $X^{(3)}$ process occurs are CdS cooled to 77 K (as yet untested) and atomic sodium vapor, which has been successfully used in the lab with both pulsed and cw lasers. Other materials with large $X^{(3)}$ yet without the advantage of resonant enhancement include CS_2, PTS polydiacetylene, and 2-methyl-4-nitroanilene (MNA). Of these, phase conjugation has been demonstrated elsewhere in CS_2 with a pulsed Nd:YAG laser, though attempts on MNA in this lab

with a cw argon ion laser have proven unsuccessful. The high diffraction efficiencies attainable in resonant media are offset by the cost of a tunable laser system and the problems involved in maintaining high quality, narrow bandwidth output. The nonresonant media require no tunability but higher energy densities are needed and so one must resort to high power laser systems such as Nd:YAG.

We have upgraded the laboratory (at no cost to the contract, by borrowing the laser from NASA Ames) to include a dye laser pumped by a pulsed nitrogen laser, a flame apparatus and an exhaust system. By midsummer all equipment was properly tested and this allowed us to investigate a novel technique for measuring species concentration in a flame using phase conjugation . The details of the technique are described in a companion paper titled: "Phase conjugation in a flame", submitted to Optics Letters. In essence, we have investigated the issues raised in the introduction and determined that indeed a quantitative measurement of species concentration can be made in a combusting environment. The technique described uses sodium as the seed material, but it should be remembered that any material which has a resonance frequency which is accessible by a laser wavelength can be used. Thus it should be possible to measure for instance OH and NO.

IV Real-time speckle velocimetry

Speckle velocimetry has been used in noncombusting flows to measure velocity in a plane. A sheet of laser light is used to illuminate a particle laden flow and scattered radiation is recorded on high resolution film. Solid state cameras cannot be used for this purpose, because of the spatial resolution required

(microns). The scattered radiation constitutes a speckle pattern on the film when the resolving power of the camera system does not allow imaging of the individual particles. Velocity information can be obtained by superimposing two speckle patterns on the same film. Upon development the film is illuminated by another laser beam and Young's fringes result in the far field diffraction pattern. The fringe spacing and orientation are directly related to the velocity vector. The fringe pattern can be analyzed using a vidicon camera system coupled to a digital computer, because the resolution requirements are not very demanding. (Fractions of a millimeter). The technique described here thus provides velocity measurements in a plane at an instant in time. We have proposed to use nonlinear optical materials for the recording of these speckle patterns, thus providing real-time capability for the first time. The crystal is used as a storage device for the speckle patterns, which can be recorded during the pulsetime of the laser. It is also possible to record multiple exposures and thus provide a time-sequences of velocity at repetition rates in excess of thousands of frames per second. The total number of frames that can be stored should , in principal, be on the order of hundreds, and is limited by the achievable signal-to-noise ratio. However, combusting flows with appreciable heat release cause the scattered rays from the particles to bend. This in turn limits the resolution of the recorded speckle patterns as well as the similarity of the patterns which are recorded sequentially. Since we need to compare two similar, but displaced speckle patterns in order to determine the velocity field, we need to investigate this ray bending or distortion problem, which can be particularly severe in a combusting environment (as opposed to a noncombusting gas flowfield). In addition we need to investigate the time-

response and photorefractive sensitivity of the recording medium.

4.1 Progress

The effort described here constitutes recording double-exposed specklegrams of a low speed air jet seeded with smoke, and making quantitative measurements in a simplified case. Work leading up to these results consisted of setting up the laboratory and acquiring and constructing optical and support equipment specifically for this research.

Tha laser used for these experiments is a Nd-Yag laser. The most important mode of operation of the laser for the speckle velocimetry research is the double pulsed Q-switch mode which produces two very short (8 nsec) pulses. The relative energies of the two pulses vary greatly with respect to separation time and total energy of the two pulses, but careful calibration allows a useful range of pulse separations of 40-140 microseconds.

Construction of the air jet and set-up of the jet, smoke generator, laser sheet, and imaging optics or camera provided the means for producing double exposed specklegrams of a flow. Analysis of these preliminary data has proved more complex than anticipated; the practical implementation of Fourier analysis of double exposed random patterns (specklegrams) is a careful balance of interrogating beam size, particle size and density, laser sheet intensity, and other lesser practical considerations. This balance has been achieved for a few specklegrams. In addition we have studied a calibration experiment which produced excellent results. In these experiments the smoke flow is replaced by a ground glass plate which is translated by a measured amount between exposures. This produces a

double exposed specklegram of a uniform displacement field, which is a simplification of the widely varying displacement field of a jet. From this simplified case optical analysis repeatedly produced Fourier transforms of excellent signal-to-noise ratio from which the displacement was calculated to within 1 micrometer of a 100 micrometer displacement. An example of the quality of the results attainable is shown in Figure 3.

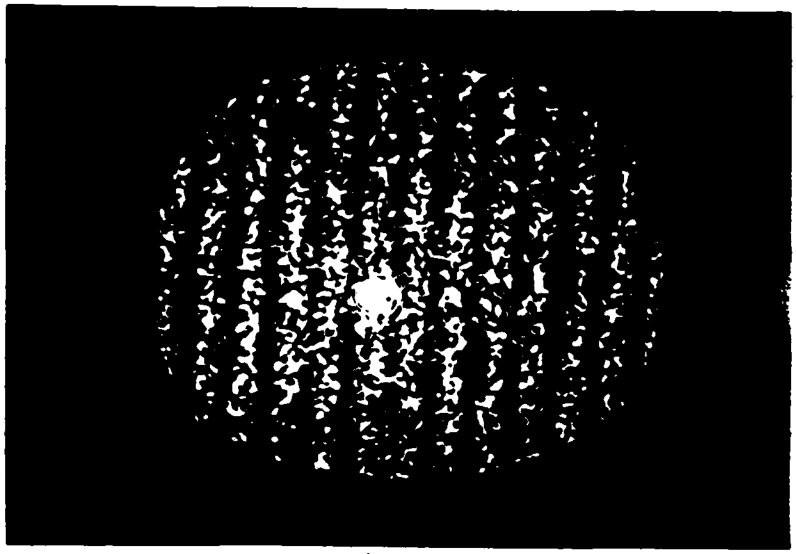

Figure 3. Example of an optically Fourier transformed double exposure specklegram

Current work is concentrated on reliably applying optical Fourier analysis to the specklegrams of the jet. Once this is achieved, this anemometer can be made to perform in real time by the use of nonlinear electro-optic crystals as the recording medium. Also the analysis of the specklegrams can be made more accurate by applying digital image processing techniques to the results of the optical analysis. In particular we are interested in investigating the effect of combustion on the usefulness of the technique, as described above.

V. Scientific merit

The need for making planar or volumetric measurements in a combusting flow has been well established. Fluorescence is an attractive method, but often quantitative data interpretation is complicated by quenching problems. Ideally one would like to use gases which exhibit a short fluorescence time and a narrow linewidth. Unfortunately not all species of interest in combustion research satisfy these criteria. Phase conjugation offers the possibility of a complementary technique, which can provide data with a potentially high signal-to-noise ratio using low laser powers (compared with for instance Raman techniques). The technique also offers the opportunity to perform optical processing of the data such as edge detection in real-time.

The other technique investigated offers the possibility for making optical velocity measurements in a plane using optical information processing. It has become very apparent to us that digital processing is not very suitable for obtaining velocity measurements from particle streak measurements because of the extensive computational time required. Optical processing has been shown to significantly reduce the computational burden required for obtaining speckle velocimetry data. Film based systems have been used to achieve instantaneous velocity data in a plane, but the proposed technique offers the ability for the first time to make *time resolved* 2-D velocity measurements. In addition the nonlinear crystal, which allows very high resolution recording can be used to store multiple speckle patterns and thus obtain a movie of planar velocity data at a rate of at least several Khz, but probably much higher.

VI. Publications and presentations

1 Digital reconstruction methods for three-dimensional flow visualization, Proc. SPIE, 507, 1984

2 Phase conjugation in a plane, submitted to Optics Letters

3. Quantitative three-dimensional flow visualization, submitted to Physics of Fluids.

Presentations.

1. Digital image processing in fluid mechanics, invited lecturer responsible for three days of teaching at a one week short course at the Von Karman Institute, NATO, Brussels, Belgium, March 1984.
2. Three-dimensional displays, invited lecturer of a 1/2 day course on this subject matter, SPIE, august 1984.

VII. Personnel

Lambertus Hesselink, Assistant Professor, Aeronautics and Astronautics and Electrical Engineering Department.

John Pender, Graduate student in Applied Physics.

Steve Collicott, Graduate student in Aeronautics/Astronautics (not supported by contract because he holds a Fellowship)

Juan Agui, Graduate student in Aeronautics/Astronautics (not supported by contract because he holds a Fellowship).

2.7 New Techniques

The major goal of the Stanford Program is the innovation of modern, primarily laser-based diagnostic techniques appropriate for the characterization of reacting flows and plasmas. This program is viewed as a multi-year effort, and as such we focus a portion of our effort each year on the preliminary investigation of new techniques. Ideas receiving attention during the past year include: (1) visualization of pressure and vorticity; (2) visualization of CO, H and O concentrations using two-photon fluorescence; (3) laser chemistry of high temperature gases; and (4) laser energy transfer in high temperature gases and plasmas by linear and non-linear absorption. These activities are discussed briefly below.

Pressure and vorticity are flowfield variables of primary importance that have not, to our knowledge, been measured optically. The vorticity, a vector quantity given by the curl of the velocity vector, is a measure of the rotation of the fluid and should in principle be accessible from velocity visualization data by evaluating the appropriate velocity gradients. Given velocity visualization of sufficient accuracy to allow differencing of velocity components between adjacent pixels, the calculation of vorticity and subsequently its display should be straightforward. The major obstacle to visualizing vorticity is thus the availability of velocity data of sufficient accuracy. Accordingly, we have set out to upgrade our velocity visualization experiment, and with the acquisition of the High Resolution/High Dynamic Range camera system in the next few months we expect to be able to obtain velocity data of suitable quality to perform vorticity visualization.

The optimum strategy for visualizing pressure is less obvious. However, our current two-frequency scheme for multiple-point velocity measurements (see Sec. 2.4) appears to offer exciting promise for determining pressure and velocity simultaneously. The key is that the PLIF data acquired in the two-frequency scheme also can be processed (by simple combinations of the four signals obtained at each pixel) to yield a value for the slope of the absorption lineshape function, and this quantity is primarily dependent on pressure at certain positions within

the absorption line. To illustrate the possibility of this approach, we have plotted calculated values of the inverse of the lineshape function (in normalized form, i.e. $g/(dg/d\nu)$) for I_2 as a function of pressure: see Fig. 1. We see that over the range of temperature and pressure used in our current experiments this slope function, obtained directly from the PLIF data, is a strong function of pressure. We plan to propose further work on this promising combined pressure-velocity concept in our forthcoming proposal. The approach should be of special value in studies of supersonic and hypersonic flowfields

The second new technique under consideration is two-photon fluorescence of CO, O and H. In this process, VUV absorption transitions of these species are accessed by combining two (or more) UV photons, and the subsequent decay of the upper state is monitored by fluorescence, usually in the visible. The major disadvantages of this approach have been the low efficiency of the process, requiring high laser pulse energies to yield suitable signals, and the inherent difficulty of calibrating the system given the spatial and temporal variations in laser intensity coupled with the non-linear response of the gases. During the past year, however, good progress has been made in other laboratories in developing single-point, two-photon LIF schemes for these species, and in one case (Alden et al. in Sweden) measurements of CO have been made with an intensified linear array. The combination of advances in laser and detector technology with improved understanding of the two-photon spectroscopy of these species (and in particular the optimum wavelengths for excitation and detection) now suggests that quantitative visualization using two-photon processes is feasible. At present we are planning toward visualization of CO using two-photon excitation of the $B \leftarrow X$ system with detection of subsequent $B \rightarrow A$ emission. Work underway includes: modifications to our Nd:YAG-pumped dye laser system to achieve higher output energies at the pump wavelength, λ=230 nm, and construction of a multi-pass illumination system to provide increased illumination intensities. We have devised a calibration scheme to deal with the problem of nonuniform illumination and hope to attempt a demonstration experiment within three months.

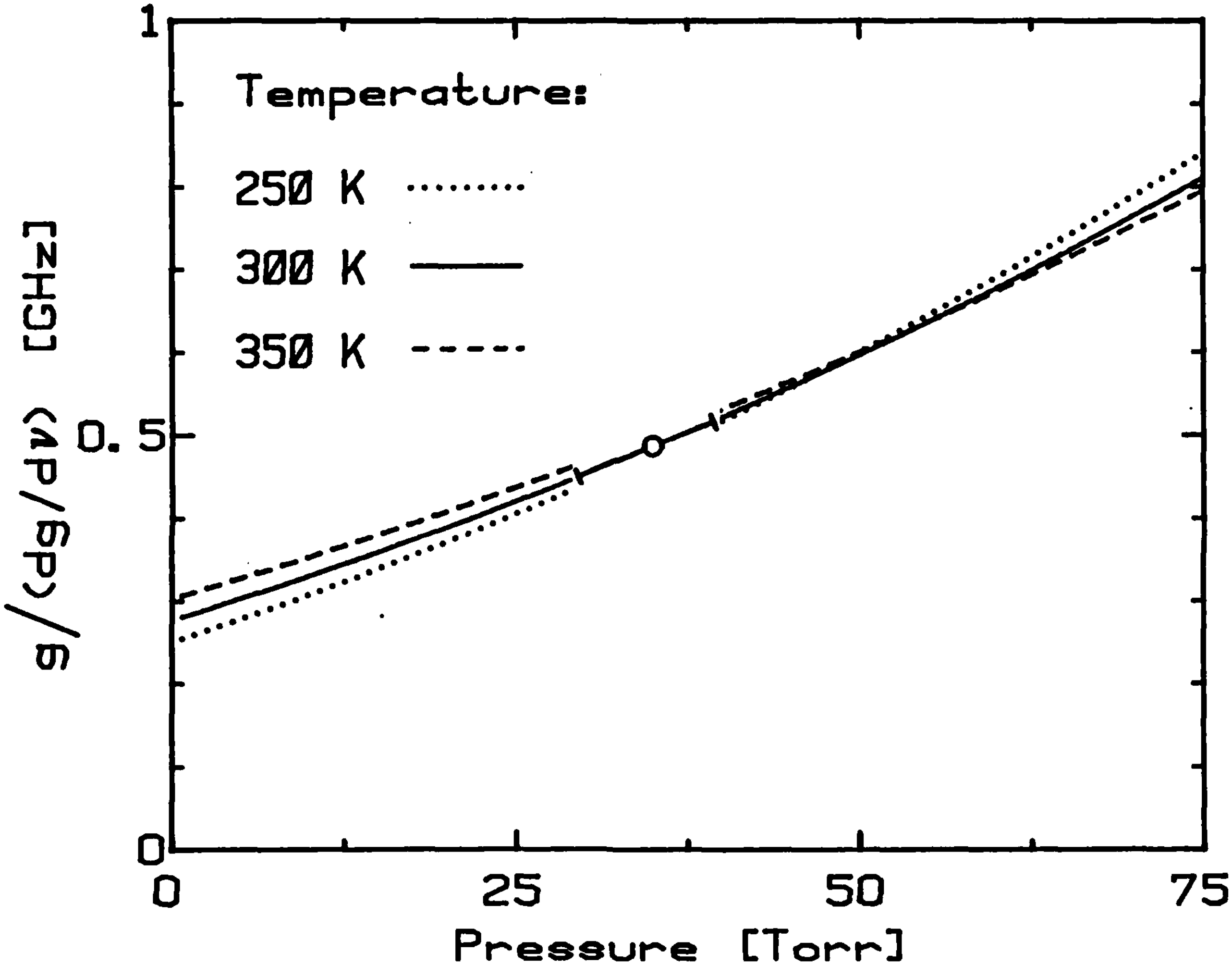

Fig. 1 Normalized absorption lineshape function for I_2 as a function of pressure.

Our third new area of interest is laser chemistry in high temperatures gases. The idea is to employ our new excimer laser as a pulsed high-energy source of UV and VUV photons (operating wavelengths include 308 nm, 248 nm and 193 nm) which can break molecular bonds and perturb the chemical composition of combustion gases or plasmas. We foresee that experiments of this type will lead to new techniques for detailed probing of the nonequilibrium behavior of high temperature gases and to fundamental studies of energy conversion processes, as related for example to laser propulsion concepts. At present we are assembling a room temperature flow cell with optical ports for exciting and monitoring the response of gases such as NH_3, N_2O and H_2O. These are species which are convenient to handle and are known to decompose upon illumination with UV or VUV sources; hence this work will provide a good starting point. Subsequently we hope to extend our experiments to include very high temperature gases in a shock tube and in a plasma torch, and we expect that such work will form a part of our proposal for FY 86.

Finally, we have given some thought to experiments aimed at studies of laser energy transfer in high temperature gases, particularly plasmas, under conditions where non-linear absorption phenomena or induced motion of the gases occurs. This work relates to the project above, on laser-stimulated chemistry, but has a different emphasis--namely high levels of energy transfer under extreme conditions. Our tentative plan is to include work along these lines in our upcoming proposal. Laser sources would include pulsed Nd:YAG at 1.06 μm, pulsed excimer (at 308 nm, 248 nm, 193 nm and 179 nm) and possibly pulsed CO_2 at 10.6 μm. The gases could be produced in the reflected shock region of a shock tube or in a plasma torch; diagnostics would be based on absorption emission and fluorescence spectroscopy.

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